APTD 0702

PB 201 216

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IITRI Project C6187
COOLING TOWER STUDY
Final Report
Contract CPA 22-69-122

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124

PB201 216

BIBLIOGRAPHIC DATA SHEET	1. Report No. APTD-0702	2.	3. Recipient's Accession No.
4. Title and Subtitle Cooling Tower Study			5. Report Date January 1971
			6.
7. Author(s) John Stockham			8. Performing Organization Rept. No.
9. Performing Organization Name and Address IIT Research Institute Technology Center Chicago, Illinois 60616			10. Project/Task/Work Unit No.
			11. Contract/Grant No. CPA 22-69-122
12. Sponsoring Organization Name and Address Environmental Protection Agency Air Pollution Control Office 411 W. Chapel Hill Street Durham, North Carolina 27701			13. Type of Report & Period Covered Final
			14.

15. Supplementary Notes

16. Abstracts

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17. Key Words and Document Analysis. 17a. Descriptors

Cooling towers
Airborne wastes
Water vapor
Effluents
Electric power generation
Climatology
Plumes
Diffusion

17b. Identifiers/Open-Ended Terms

Natural draft cooling towers

17c. COSATI Field/Group 13B

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Unlimited	UNCLASSIFIED	123
	20. Security Class (This Page) UNCLASSIFIED	22. Price

FORM NTIS-35 (10-70)

USCOMM-DC 40329-P71

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IIT Research Institute
Technology Center
Chicago, Illinois 60616

in fulfillment of Contract No. CPA 22-69-122

IITRI Report No. C6187-3
(Final Report)

COOLING TOWER STUDY

June 23, 1969 through June 22, 1970

Contract No. CPA 22-69-122
IITRI Project C6187

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Environmental Protection Agency Air Pollution Control Office
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Attention: Dr. James Peterson

January, 1971

Final Report C6187-3

FOREWORD

This Cooling Tower Study was performed under Contract No. CPA 22-69-122 by the IIT Research Institute during the period June 23, 1969 to June 22, 1970. The project was sponsored by the Division of Meteorology, Air Pollution Control Office, Environmental Protection Agency, 3820 Merton Drive, Raleigh, North Carolina, 27609. The program was monitored by Dr. James T. Peterson. The project leader at the IIT Research Institute was Dr. Eric Aynsley. The plume modeling studies were conducted by Dr. Hugo Nielson; Mr. W. Boynton Beckwith evaluated the local climatological effects. Mr. Beckwith was a consultant to IIT Research Institute.

Dr. Aynsley acknowledges the assistance of Mr. K. Gray and other staff members of the Keystone Station, Mr. Frank Schiermeier of the Air Pollution Control Office, the Keystone Helicopter Corporation, Philadelphia, Pennsylvania, and the Analytical Services Corporation, New Castle, Delaware.

Respectfully submitted,
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ABSTRACT

COOLING TOWER STUDY

The purpose of this study was to describe and evaluate the potential effects that the emissions of water vapor and heat from natural draft cooling towers have on the local environment, climate, and nearby electrical power station emissions. Field tests were conducted at the Keystone generating station near Shelocta, Pennsylvania. Observations and measurements were made intermittently during September, November, and December 1969.

Natural draft cooling towers are being selected with increasing frequency by the electrical power utilities to dispose of their waste heat. Currently there are 18 such towers in operation and between 32 and 40 will be operational by 1974. These towers will be located predominantly in the Northern Appalachian area; 22 will be in Pennsylvania.

Although cooling towers have the potential to produce fog and drizzle, to initiate clouds, and to enhance rainfall, the Keystone Plant produced none of these adverse effects while under observation during this study. Moreover, historical precipitation records from 9 U.S. Weather Bureau stations, located between 13 and 51 kilometers from Keystone, were analyzed for possible influence from the Keystone effluent. Only in July of 1969, is there a suggestion of precipitation enhancement as a result of station operation. The monthly precipitation totals for all other months during which Keystone was in operation fall within the natural variability range for the area. Based on the observations of a resident Air Pollution Control Office meteorologist over a 12 month period, cloud initiation during periods of otherwise clear skies is infrequent. However, the cooling tower plume often merges with low stratus clouds.

Natural draft towers vent large quantities of heat and water vapor to the atmosphere. At Keystone approximately 10,000 gal/min of water are evaporated and 120 million BTU/min of heat are released when the station is operating at 80-86% of its rated 1800-megawatt capacity. During our observations the visible portion of the tower plume normally rose to an altitude of less than 200 meters and traveled downwind about 200 meters before evaporating. However, the dimensions of the visible portion of the plume were greatly dependent on the temperature and humidity of the ambient air. When temperatures were 25-30°F and the relative humidity was high, the plume could be seen for thousands of meters. Even when the plume was visible over only a short distance, its path could be traced up to 11,000 meters by aerial relative humidity measurements.

The plume travels downwind of the plant with an oscillatory motion in the vertical direction. Using inputs from the field studies, a mathematical model indicated that a plume moisture content 50% in excess of saturation at the tower exit would produce the observed oscillatory pattern.

The effluents from the power station stacks and the cooling towers at Keystone do mix. This mixing is shown by the presence of acid droplets in the visible portion of the cooling tower plume and the humidity and sulfur dioxide profiles obtained along the axis of the plume path after the humid plume had evaporated.

The full environmental effects of natural draft cooling towers can not be stated conclusively for three reasons. The station effluents were observed and sampled over a short-time period that represented only one season of the year; the station was generating power at only 1/6 of its rated capacity

during a portion of the field tests; and field instrumentation was lacking in several essential areas. It is recommended that the power station be instrumented to aid in evaluating the volume and nature of water losses, and weather stations in the vicinity of Keystone be expanded in both numbers and facilities.

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INTRODUCTION

The environmental effects produced by the discharge of large quantities of water and waste heat to the atmosphere by natural draft cooling towers are described and evaluated. Five specific tasks were performed during the course of this program. These tasks were:

Task 1 - A list of natural draft cooling towers in operation, under construction, and being planned was compiled. The data include information on tower sizes, capacities,operating characteristics, and geographical location.

Task 2 - The diffusion of heat, water vapor, and chemical carry-over emitted by natural draft cooling towers was described and evaluated. A theoretical plume diffusion model was developed and applied to the study findings.

Task 3 - The local climate modifications resulting from the increase in moisture content discharged from natural draft cooling towers were assessed.

Task 4 - The effect of the emissions from natural draft cooling towers on the chemical and physical composition of the emissions from nearby power station effluent was evaluated.

Task 5 - Possible deleterious effects on the local environment from the release of large amounts of water vapor and heat by natural draft cooling towers were listed.

Field studies were conducted at the Keystone electrical power generating station located near Shelocta, Pennsylvania. Keystone is a mine mouth, coal-fired plant with a generating capacity of 1800 megawatts. The station has twin power generating units each with a capacity of 900 megawatts. Associated with each unit is a chimney stack 244 meters in height and two natural draft, hyperbolic cooling towers, each 99 meters in height. One unit of the station went into operation in 1967; the second unit was placed on stream in 1968. The plant, its site, the local climatology,

and the operation of the cooling towers are described in Appendix A. Keystone was selected as a study site because of on-going studies related to power station emissions. These studies include an evaluation of tall stacks and sulfur dioxide emissions and washout effects. Also, a nearby airport provides a suitable base for aerial surveys; and the four natural draft cooling towers are the greatest concentration of such towers at a single location.

The disposal of waste heat is of great concern to the electric power generating industry. This industry must dispose of large quantities of waste heat. It is necessary to dispose of 4.4 BTUs of waste heat for every watt of generating capacity in today's design of a coal-fired steam electric power station and 6.6 BTUs for every watt in a nuclear electric station. Thus, a 1000 megawatt steam station must dispose of 1300 megawatts of waste heat; a nuclear station of similar capacity must dispose of 1950 megawatts of waste heat.

NATURAL DRAFT COOLING TOWERS: GROWTH TRENDS IN THE U.S.

Table 1 contains a summary of the natural draft cooling towers currently operating, under construction, or being planned throughout the United States. The first natural draft cooling tower was at Big Sandy near Louisa, Kentucky. It began operation in December 1962. Since this date there has been a rapid increase in the use of such cooling towers. This trend is shown in Figure 1. About 18 towers were in operation by mid 1970; projections indicate that 32 to 40 towers will be completed in two to three years. The time laspe between start and completion of natural draft cooling towers is about 24 to 30 months; for this reason, the number of towers projected beyond 1972 could be underestimated. Without exception all the towers listed are associated with the electrical utility industry. To date, all the operational towers serve coal-fired, steam electric stations, but about half of the future towers will serve nuclear stations. The vast majority of the towers are and will be located in the Northern Appalachian area, Figure 2.

There are a number of factors that currently favor the selection of cooling towers as a means of disposing of waste heat. The two most prominent factors are present economics of power station siting and antipollution regulations pertaining to both thermal and air pollution. The electrical generating industry is selecting rural sites for new stations and mine mouth locations for coal-fired units because the cost of overland power transmission is more than offset by the lower rural property values and bulk fuel transportation costs. The lack of large bodies of water at these sites and the antipollution regulations dictates the use of either forced or natural draft cooling towers. As shown in Appendix A, the climatic conditions favorable to the efficient use of natural draft towers are low ambient temperatures and high relative humidities. Also, the natural draft capacity and power demand ideally should be in phase. These factors pre-

TABLE I

SUMMARY OF U.S. NATURAL DRAFT COOLING TOWERS

PROJECT			ELECTRIC STATION		NATURAL DRAFT TOWERS			TOWER			TOWER DESIGN BASIS				
			Size	Type C-Coal N-Nuclear	Number	Cum. Total	Start-Up Date	Height Meters	Base Dia. Meters	Total Water Flow, gpm x 10^3 (1)	Range °F (2)	Approach °F (3)	Wet Bulb °F	Dry Bulb °F	Relative Humidity %
Plant	Location	Utility	MW												
Big Sandy #1	nr. Louisa, Ky.	Kentucky Power AEP	265	C	1	1	Dec. 1962	98	74.5	120	22.7	15	72	79.5	70
Keystone #1 & #2	nr. Shelocta, Pa.	Pennelectric Keystone Group	2 x 900	C	4	5	Spring 1967	99	75.2	560	28	18	72	86.5	50
Ft. Martin #1	nr. Morgantown, West Virginia	Alleghany Power	540	C	1	6	Spring 1967			250					
Ft. Martin #2		Duquesne Power	540	C	1	7	Spring 1968	113	115	250	24	18	72	86.5	50
Paradise #1,2&3	Green River, Ky.	TVA	2 x 700 1150	C	3	10	Spring 1968	133	97.5	260	27.5	22.6	72.6	78	78
Muskingum River	nr. Beverly, Ohio	Ohio Power AEP	615	C	1	11	Fall 1968	113	120	220	24	16	70	77	71
Big Sandy #2	nr. Louisa, Ky.	Kentucky Power AEP	800	C	1	12	Spring 1969	113	121	248	28.7	16	70	77	71
Homer City #1&2	Homer City, Pa.	Pennelectric, New York State E&G	2 x 640	C	2	14	Fall 1969	119	84.0	208	28	20	82	86.5	50
Conemaugh #1	nr. Johnstown, Pa.	Pennelectric, Conemaugh Group	820	C	1	15	Winter 1969	113	87.7 119	280	28	18	72	86.5	50
Mitchell #1	nr. Moundsville, Pa.	A. E. P.	800	C	1	16	Winter 1969	113	119	248	28.7	16	70	77	71
Conemaugh #2	nr. Johnstown, Pa.	Pennelectric, Conemaugh Group	820	C	1	17	Spring 1970	113	87.9	280	28	18	72	86.5	50
Mitchell #2	nr. Moundsville, Pa.	Appalachian Power	800	C	1	18	Spring 1970	113	119	248	28.7	16	70	77	71
Hatfield #3	Masontown, Pa	Alleghany Power	2 x 540	N	1	19	Winter 1970	114	100	265	18	16	72	86.5	50
Rancho Seco #1	Sacramento, Calif.	Sacramento Municipal District	850	N	1	20	1970	122	915	223	28	23	52	59.5	60
Etowah #1	-	Georgia Power	700	C	1	21	1971			258	25.6	19	76	88	58
Montour #1	-	Pa. P. & L.	785	C	1	22	1971	113		261	27.6	17	73	88	50
John E. Amos #4	Charleston, W. Va.	A. E. P.	800	C	1	23	1971	122	97.5	248	28.7	16	70	77	71
Peach Bottom #1	York County, Pa.	Philadelphia Elec.	1065	N	1	24	Winter 1971								
Burlington #1	Burlington, N. J.	Public Service E&G	1000	N	1	25	Winter 1971								
Etowah #2	-	Georgia Power	700	C	1	26	1972			258	25.6	19	76	88	58
John E. Amos #5	Charleston, W. Va.	A. E. P.	800	C	1	27	1972	122	97.5	248	28.7	16	70	77	71
Three Mile Island #1	Harrisburg, Pa.	General Public Utilities	830	N	2	29	1972	116	113	215	28	16	72	86.3	50
Rancho Seco #2	Sacramento, Calif.	Sacramento Municipal Utility	850	N	1	30	1972	122	91.5	223	28	23	52	59.5	60
Montour #2	-	Pa. P. & L.	785	C	1	31	1973	113		261	27.6	17	73	88	50
Peach Bottom #2	York County, Pa.	Philadelphia Elec.	1065	N	1	32	Spring 1973								
Burlington #2	Burlington, N. J.	Public Service E&G	1000	N	1	33	Fall 1973								
John E. Amos #3	Charleston, W. Va.	A. E. P.	1300	C	1	34	1973	152							
Harrison	-	Alleghany Power	3 x 650	C	2	36	1973								
Three Mile Island #2	Harrisburg, Pa.	General Public Utilities	830	N	2	38	1974	116	113	215	28	16	72	86.3	50
Trojan	Columbia River, Ore.	Portland General Electric	1118	N	1	39	1974	152		130					
Unspecified		A. E. P.	1300	C	1	40	1974	152							
Etowah #3	-	Georgia Power	875	C	1	41	1974	122							
Martins Creek #1	-	Pa. P. & L.	800	C	1	42	1974	113		261	27.6	17	73	88	50
Limerick #1	-	Philadelphia Elec.	1100	N	1	43	1975	152							
Newbold #1	-	Public Serv. Elec.	1100	N	2	45	1975	122							
Unspecified		A. E. P.	1300	C	1	46	1975	152							
Martins Creek #2	-	Pa. P. & L.	800	C	1	47	1975	113		261	27.6	17	73	88	50
Homer City	Homer City, Pa.	New York State E&G	640	C	1	48	Proposed 1976			Addition to present plant expected					
Unspecified		A. E. P.	1300	C	1	49	1976								
Limerick #2	-	Philadelphia Elec.	1100	N	1	50	1977	152							
Newbold #2	-	Public Serv. Elec.	1100	N	2	52	1977	122							

(1) Rated capacity.
(2) Temperature difference between hot water in and cold water out.
(3) Temperature difference between cold water out and inlet air wet bulb.

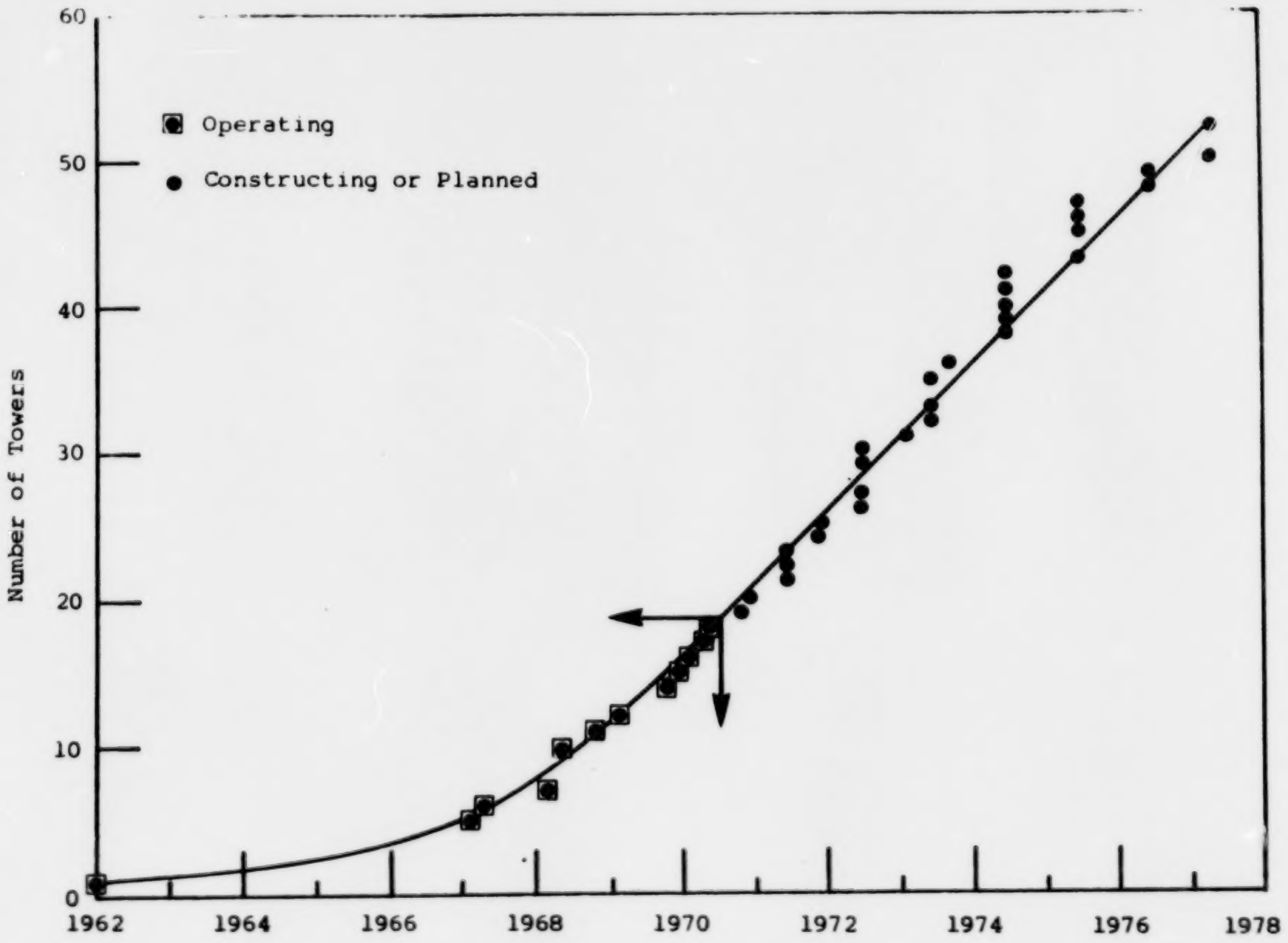


Figure 1: Number of Natural Draft Cooling Towers in the United States.

Figure 2: Locations of Natural Draft Cooling Towers Through 1977.

viously have limited the use of natural draft towers to Europe where the low ambient temperature and high humidity prevail in the winter when power demand is at its peak. In the United States peak power demand is in the summer due to the widespread use of air conditioners. As a result, mechanical draft units are favored in the States. However, the economics of the two types of cooling towers favor the selection of natural draft towers in certain situations especially for electrical power plants, where large volumes of water must be cooled.

Although this study concerns hyperbolic towers a number of electrical utilities operate large mechanical draft units on condenser cooling service. Some of the utilities employing mechanical draft units are:

American Electric Power Service Corporation
Arizona Public Service Company
Boston Edison Company
Columbus & Southern Ohio Electric Company
Dallas Power & Light Company
Duke Power Company
Georgia Power Company
Gulf States Utilities Company
Houston Light & Power Company
Iowa Electric Light & Power Company
Kentucky Utilities Company
Oklahoma Gas & Electric Company
Public Service Company of Colorado
South Carolina Electric I Gas Company
Southern California Edison Company
Southwestern Public Service Company
Texas Electric Service Company
Texas Power & Light Company
United Illuminating Company
Utah Power & Light Company

Generating stations currently under construction for which mechanical draft towers are to be used include the Monticello, Allen S. King, and Prairie Stations of the Northern States Power Company; the Altamaha River Station of the Georgia Power Companies; the Centralia station of the Pacific Power & Light Company; and the Trenton Channel Station of the Detroit Edison Company.

LOCAL CLIMATE MODIFICATIONS RESULTING FROM THE KEYSTONE TOWERS

It is postulated that the discharge of vast quantities of water vapor and heat to the atmosphere from natural draft cooling towers would modify the climatology of the region. In order to determine if the Keystone plant has produced any noticable effect during its short period of existence, the available climatological data for a 10 year period were studied.

Keystone is located rurally and is distant from a first-order U.S. Weather Bureau station having long-term climatological records for the several meteorological elements required to assess the effect of the cooling tower plumes. Precipitation data, however, are available from records maintained by the U.S. Weather Bureau and other recording and non-recording weather stations. Precipitation, therefore, is the only element that could be evaluated for any possible effect of the plume. Elements such as fog frequency, changes in relative humidity, hours of sunshine, days with precipitation, and thunderstorms would have to be evaluated to determine the full effect of the plume.

Precipitation data sources consulted in this study included:

1. Monthly and Annual Local Climatological Data issued by the U.S. Department of Commerce, ESSA Environmental Data Service.

2. World-Wide Airfield Summaries compiled by the U.S. Naval Weather Service.

3. The Office of the State Climatologist (ESSA-U.S. Weather Bureau) at Pennsylvania State University. Stations for which climatological data at this office were studied and tabulated are shown in Figure 3. Station vital statistics are tabulated in Table 2.

4. The complete data record for the Greater Pittsburgh Airport was used to establish a control for the area under study and to determine the monthly and annual prevailing wind.

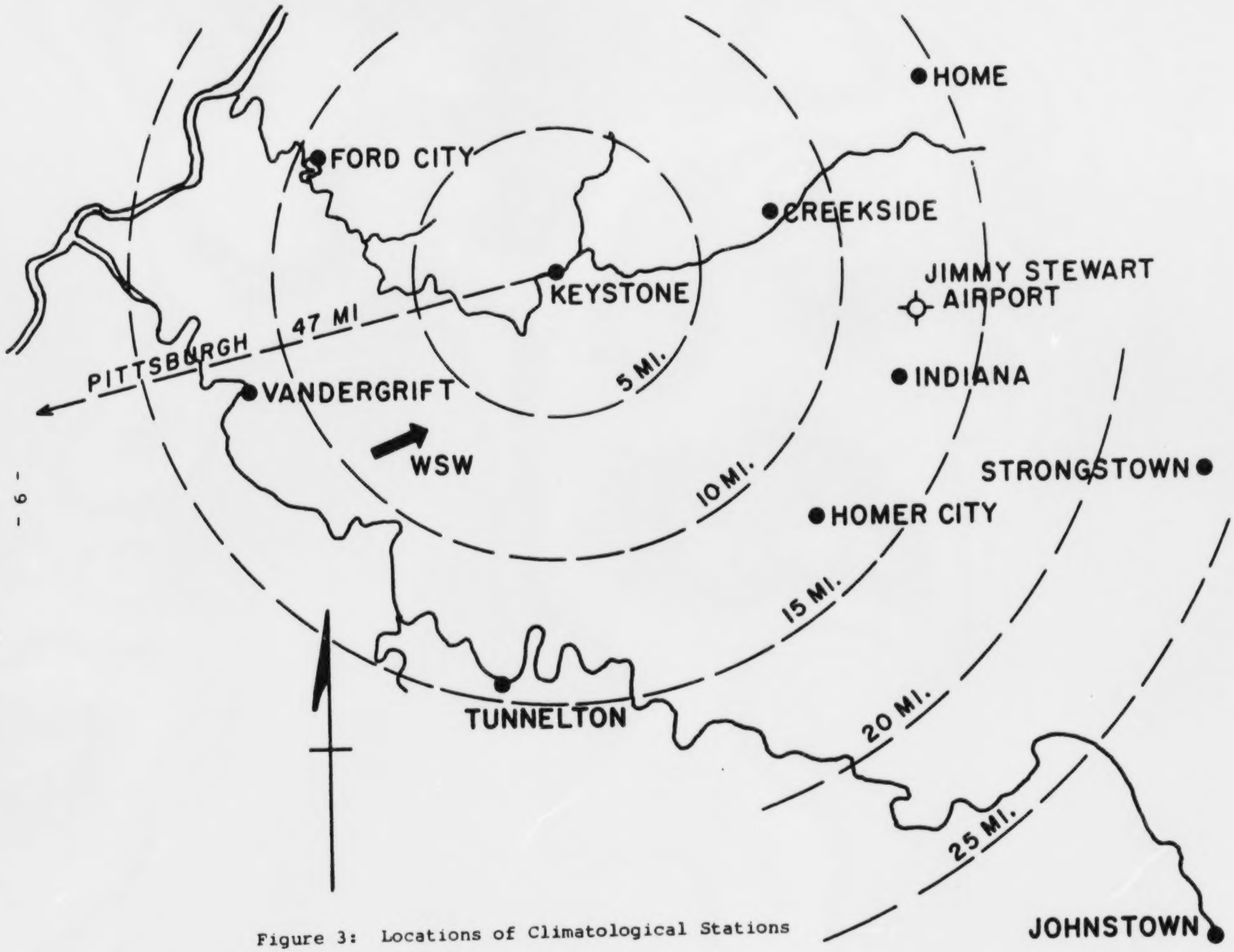


Figure 3: Locations of Climatological Stations

Table 2

VITAL STATISTICS OF STATIONS USED IN THIS STUDY

Station	Location from Keystone Miles	Direction	Elevation (meters)	Type of Record
Creekside	8	ENE	314	Non-recording rain gauge
Ford City Dam	9	NW	290	Recording rain gauge
Home	14	ENE	372	Recording rain gauge
Indiana	12	ESE	336	Recording rain gauge
Johnstown	32	SE	389	Recording rain gauge
Strongstown	24	ESE	572	Recording rain gauge
Tunnelton	14	S	272	Recording rain gauge
Vandergrift	12	WSW	244	Non-recording rain gauge
Greater Pittsburgh Airport	47	WSW	346	Complete observations

The precipitation records for the stations shown in Figure 3 were analyzed for evidence of possible precipitation enhancement. The annual precipitation totals for each station for the years 1960-1969 are given in Table 3 and plotted in Figure 4. For the period 1960 to mid-1967, the precipitation pattern was not influenced by the Keystone Station, since this facility went on stream at partial capacity in the spring of 1967 and at full capacity in mid-1968. The annual prevailing wind for Pittsburgh each year during the 10-year period (1960-1969) was SSW. On an annual basis, then, Creekside and Home are downstream from Keystone and any large scale climatological effects should show up at these two reporting stations. From Figure 4, it is apparent that no such effects are evident. The 1968 and 1969 precipitation totals fall off sharply in agreement with the Pittsburgh control data, and with the other stations for which data totals are available. These two relatively "dry" years are within the limits of variability expected with changing synoptic scale weather patterns.

To establish the existence of any seasonal pattern of influence from Keystone, the data were analyzed on a monthly basis. These are plotted as Figure 5. If any anomalous convective activity generated from the stacks and cooling towers is a significant factor on precipitation patterns, it would be expected to show its strongest effect during the spring and summer months. Prevailing surface winds for Pittsburgh for each month in 1968 and 1969 were considered in evaluating the precipitation data. Also considered was the mean monthly wind direction for the 700 mb level, because the movement of large convective cells are governed more by upper level flow than surface winds. The mean monthly 700 mb charts (Reference 1) were the source of this information. Since flow aloft tended to be from the W or even WNW during some of the spring and summer months, the Indiana and Strongstown reporting stations assume importance in assessing downwind effects. The Strongstown monthly means for the 8 years 1960-67 plotted on

Table 3

ANNUAL STATION PRECIPITATION BY YEARS

(Inches)

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
Creekside	37.36	41.47	37.65	36.78	43.90	42.20	44.63	47.87	36.01	30.13
Ford City	38.89	39.76	36.80	29.44	41.91	34.77	39.61	40.85	34.27	Inc (1)
Home	36.72	38.71	35.38	34.17	38.52	36.90	39.73	42.61	38.10	37.92(2)
Indiana	39.44	43.68	42.57	32.09	38.77	34.78	37.75	40.84	31.99	36.53(2)
Johnstown	40.30	43.55	44.19	35.98	40.34	34.81	39.40	42.31	37.01	37.97
Strongstown	39.51	50.07	40.86	36.43	42.43	40.21	42.79	50.91	42.95	Inc (1)
Tunnelton	34.98	38.49	39.92	29.56	41.05	32.97	34.65	41.43	Inc (1)	Inc (1)
Vandergrift	30.26	39.35	39.61	31.44	42.36	33.49	36.30	39.03	Inc (1)	Inc (1)
Pittsburgh(3)	31.29	38.10	31.62	26.79	37.89	30.24	34.06	36.38	36.07	29.58

(1) Incomplete.
(2) Annual total estimated - some monthly data incomplete.
(3) Used as a control.

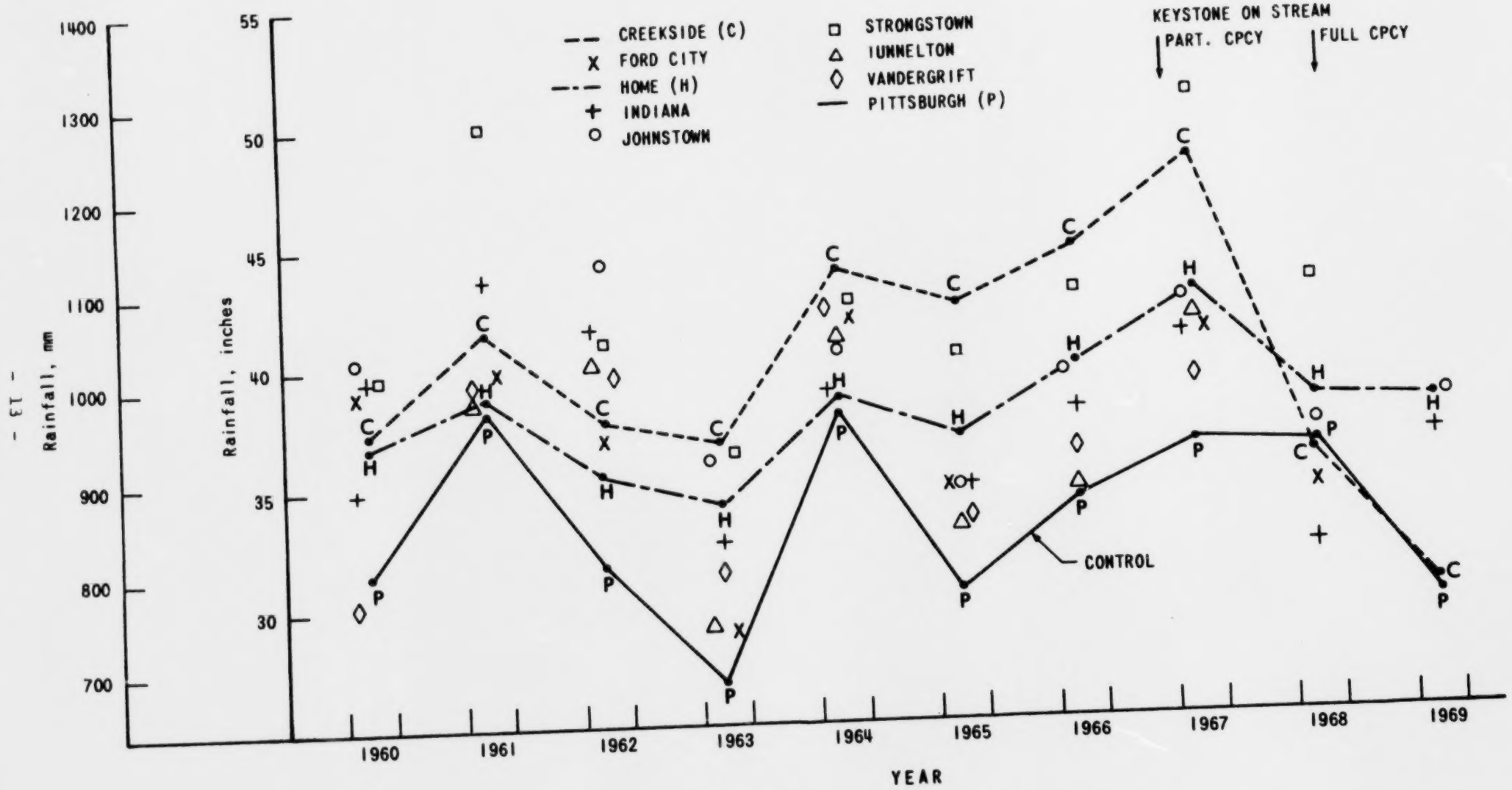


FIG. 4 STATION ANNUAL PRECIPITATION TOTALS
1960 THROUGH 1969

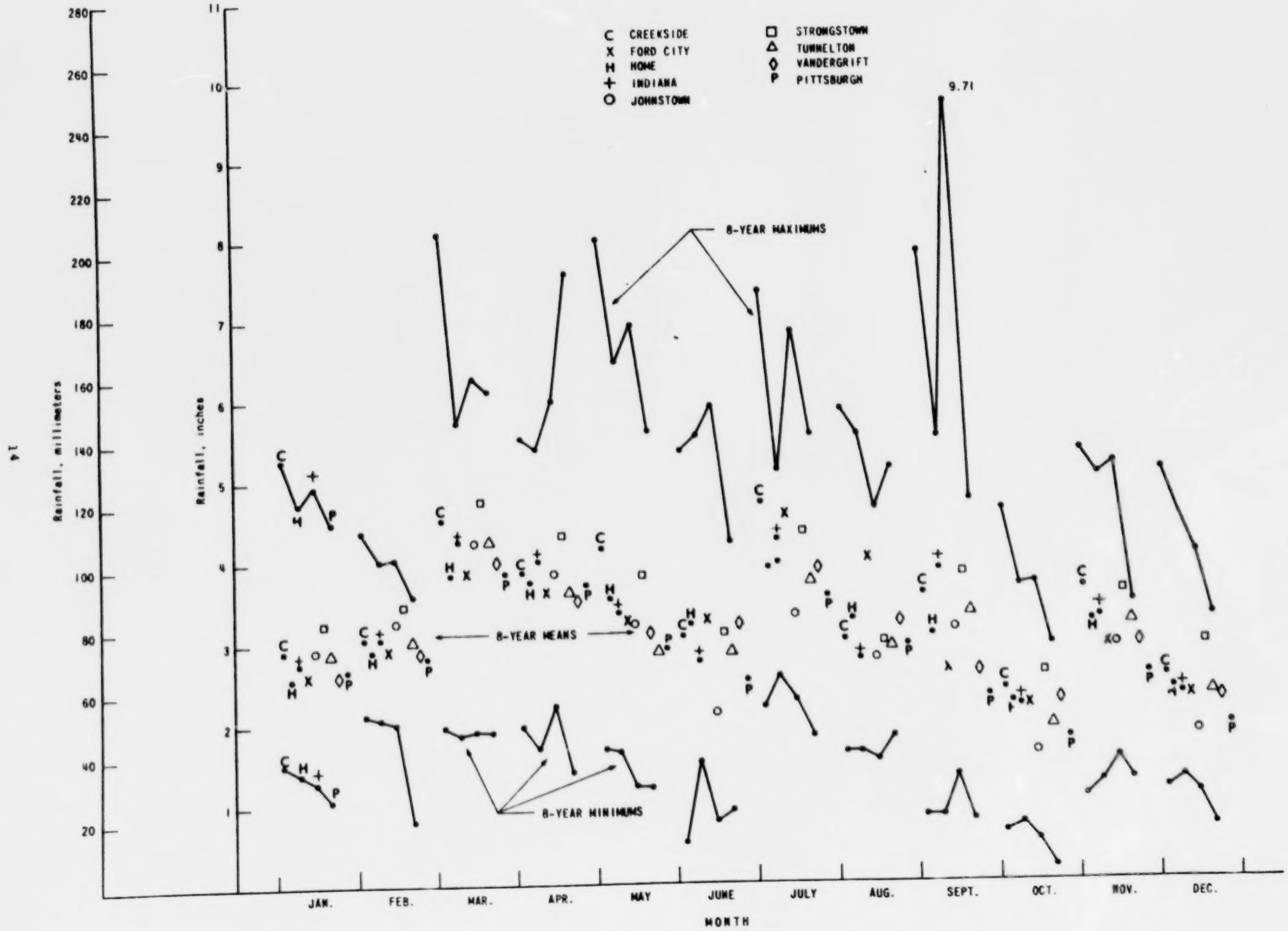


FIG. 5 STRATIFICATION OF STATION PRECIPITATION DATA: 1960 - 1967

Figure 5 run slightly higher than the other stations during the winter and spring months. This tendency is probably caused by the stronger orographic effects at the site which is 180 to 305 meters higher than the other stations. Because of this factor, Strongstown is not included in the plot of maximum and minimum precipitation values in Figure 5.

Monthly precipitation data for 1968 and 1969, when the Keystone Station was in operation, are shown in Figure 6. The maximum and minimum monthly precipitation totals recorded during the 8 years prior to Keystone going on stream are repeated in Figure 6 for reference points. If Keystone's steam plumes significantly increased the monthly precipitation at the downwind stations, the fact should be reflected in the monthly totals for Creekside, Home, and Indiana, provided a similar increase did not occur at Pittsburgh. It can be seen that in April 1969, a trend towards increased precipitation was indicated; but the values did not exceed the 8-year mean (Figure 5) by more than 0.75 inch. In July 1969 the records of Home and Indiana exceeded the 8-year extremes substantially. However, Creekside was 1.25 inches greater than the 8-year mean for July; and Pittsburgh exceeded its mean by 0.95 inch.

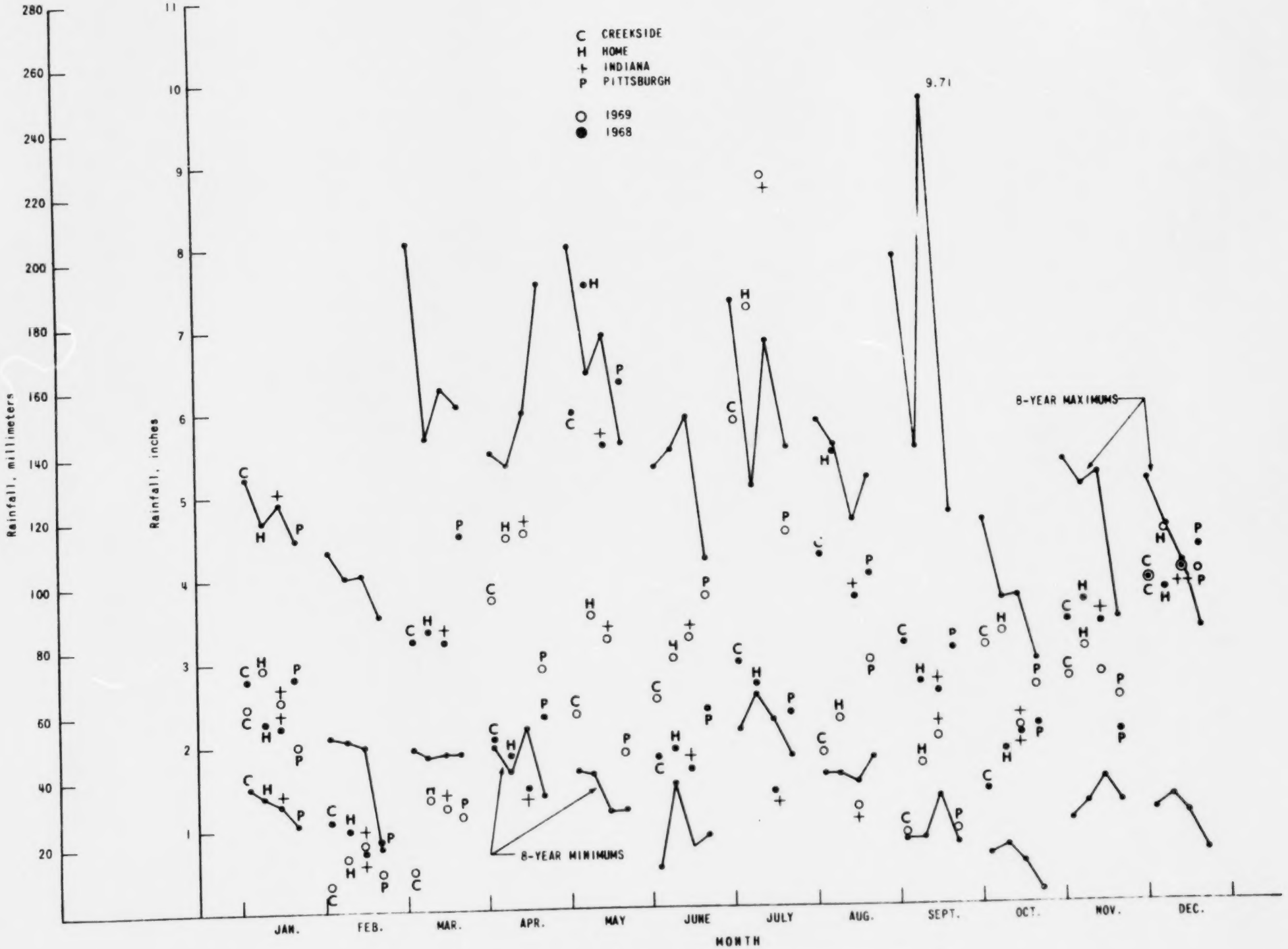


FIG. 6 STRATIFICATION OF STATION PRECIPITATION DATA: 1968 - 1969

DIFFUSION OF HEAT AND WATER VAPOR; PLUME PROFILES

The heat and water vapor released to the atmosphere by the Keystone cooling towers is given in Table 4. The data were obtained from the monograph, Figure A-3, using pump pressures to determine water flows and temperature data to obtain the cooling tower range and the relative humidity of the ambient air. The procedure is described in Appendix A. When the station was operating at 80 to 86% of its rated capacity, approximately 10,000 gal/min of water were evaporated; and the total heat released was about 120 million BTU/min. Unfortunately, at the time the most complete aerial survey data was obtained, December 6, 1969, the station was operated at 16% of its rated capacity; only one generating unit was in use. On this day, it was estimated that the two cooling towers in use released 1880 gal/min of water vapor and 28 million BTU/min of heat. On December 2, 1969, when a partial aerial survey was made, all four towers were in operation and 120 million BTU/min of heat were released. Evaporation rate on this date was 8950 gal/min. Because some pressure gauges were in error the values reported are reasonable estimates only. Also, the use of the monograph ties the results to design data rather than performance measurements. Because of the dependency of natural draft cooling tower performance on climatic conditions, the data should not be extrapolated to other seasons. Future tests of tower emissions should follow the testing technique described in British Standard 4485 (1969); this standard was not available in time for use during this study.

The visual portion of the cooling tower plumes were observed from the ground during the period of November 24 to December 7, 1969. Usually the visible portion of the plumes rose to an altitude of less than 200 meters and was less than 200 meters in length. However, the visible portion of the plume was

Table 4

HEAT AND WATER VAPOR RELEASED TO ATMOSPHERE AT KEYSTONE(1)

Date	Power Generated % of rated capacity	Number of Towers in operation	Total Evaporation loss gpm	Total heat Released 10^6 BTU/Min
9/20/69	84	4	9480	112
9/21/69	63	4	6920	84
9/22/69	73	4	8380	98
9/23/69	85	4	9760	113
9/24/69	86	4	9890	115
10/28/69	85	4	11080	145
11/29/69	80	4	9440	127
11/30/69	83	4	9550	130
12/2/69	77	4	8950	120
12/5/69	13	2	1640	22
12/6/69	16	2	1880	28

(1) Data are a summary of Table A-3, Appendix A. The method for calculating evaporation loss is described in Appendix A.

dependent on the temperature and humidity of the ambient air. When temperatures were 25-30°F and the relative humidity was high (80%), the visual portion of the plume persisted for many miles and could be seen to merge with the stratus cloud cover. At higher ambient temperatures and lower relative humidities, the visible plume attained altitudes of less than 200 meters and downwind distances of 100 to 200 meters.

Aerial surveys of the plume were made on December 2 and 6, 1969. The surveys were made with a helicopter instrumented to measure the dry bulb and wet bulb temperatures, relative humidity, sulfur dioxide, and the size and acidity of the plume droplets. The instrumentation, flight procedures, and results, with one exception, are given in Appendix B. The data obtained during the morning of December 6, 1969, are discussed in the following paragraphs. Because of turbulence, flights through the visible portion of the plume were not possible; the droplet samples were obtained at the edge of the visible portion of the plume.

The aerial survey on the morning of December 6, 1969, was initiated with a vertical ascent upwind of the Keystone Station. The aircraft then proceeded downwind of the station and sampled the invisible portion of the plume at downwind distances of 640, 4800, and 10,800 meters. Finally, the aircraft backtracked to the station at treetop level beneath the plume. The upwind ascent data are shown in Figure 7. A temperature inversion just under 600 meters was present. A marked decrease in the relative humidity and increase in the wet bulb depression coincided with the inversion. The sulfur dioxide concentration decreased with altitude; it was about 0.03 ppm at ground level and less than 0.01 ppm at 600 meters. The relative humidity up to about 550 meters was steady at about 80-85%. In the afternoon (Figure B-11), the relative humidity had dropped to 40-43%; and the temperature inversion was not detected, although the decrease in relative humidity and the increase in wet bulb depression was still observed. The profiles for air temperatures, relative humidity,

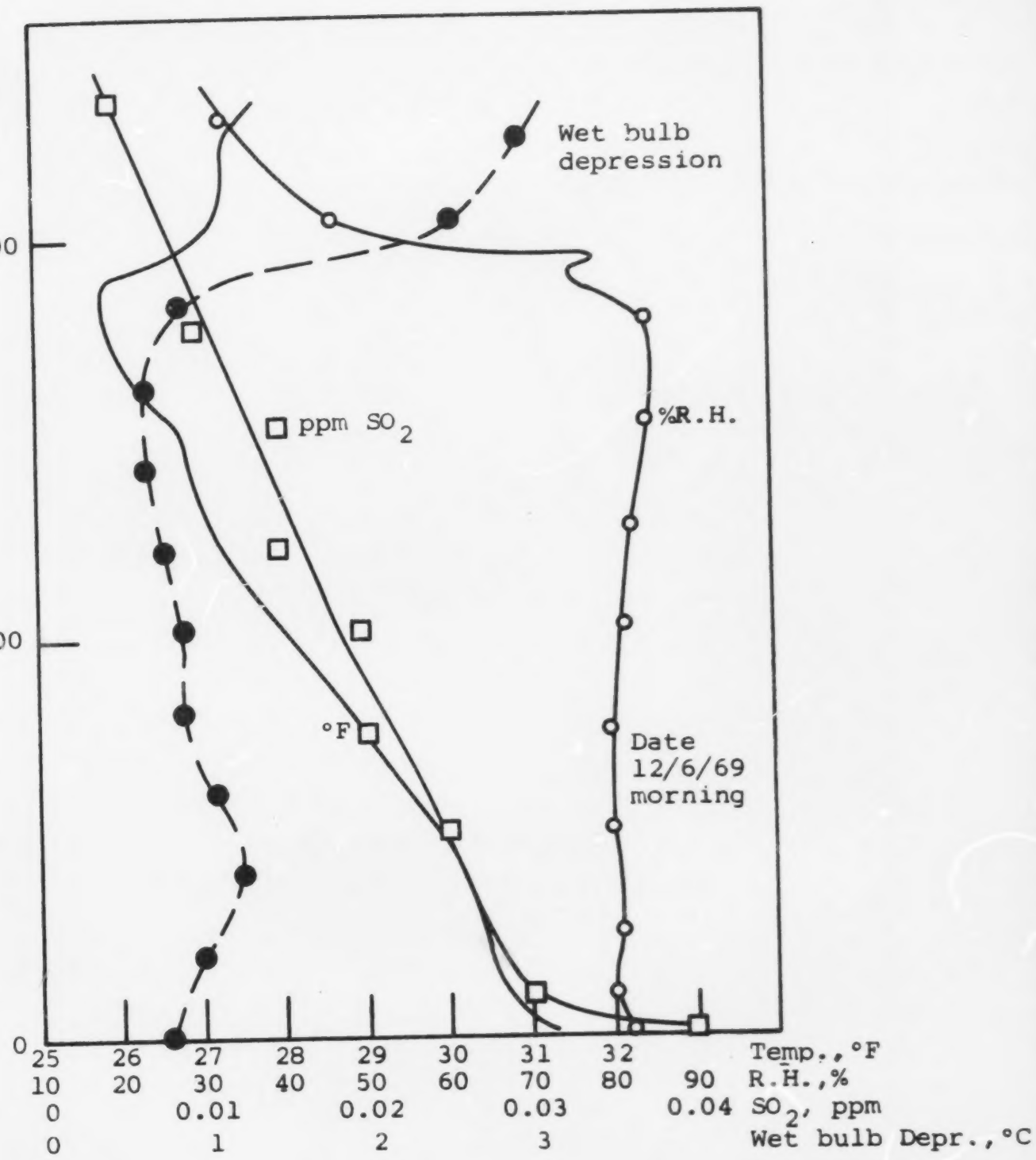


Figure 7: Prevailing Ambient Conditions Prior to Plume Traverses.

and sulfur dioxide at distances of 640, 4800, and 10,800 meters downwind of the cooling towers are given in Figures 8 through 16. The profiles were drawn as if the plume was viewed by an observer standing at the tower base and looking downwind along the plume axis. No contours were drawn through the temperature data because they appear to vary randomly and no discernable pattern could be detected. Temperatures both higher and lower than the surrounding air are indicated. The plumes vertical height oscillated from 545 to 565 to 450 meters at downwind distances of 640, 4800, and 10,800 meters, respectfully. Variations in vertical depth with downwind distance were insignificant; average plume depth was 150 to 170 meters. Horizontally, however, there was great spreading of the plume from about 2500 meters at a downwind distance of 640 meters to 5000 meters at a distance of 10,800 meters. In all instances, the humid plume was comingled with the stack plume as shown by the sulfur dioxide profiles. In Figure 17, the ambient air results beneath the plume are presented. These data were obtained about 2 hours after the upwind ascent data given in Figure 7. The most significant differences are the decrease in relative humidity from about 80% to 62% and a decrease in the sulfur dioxide concentration near to station from about 0.03 ppm to 0.017 ppm. No enhancement of the ground level humidity is indicated as a result of the overhead plume.

The plume profiles for the afternoon of December 6, 1969, Appendix B, showed similar altitude oscillations and vertical and horizontal spreadings as the morning profiles. The altitute of the plume varied from 380 to 420 to 475 meters at downwind distances of 640, 3200, and 10,800 meters. Again, the stack and tower plumes were comingled.

On December 2, 1969, all four cooling towers were in operation. The upwind ascent data, Figure B-4, show a steady decrease in temperature with altitude. Thus, no inversion was present on this date. The profiles indicate a vertical as well

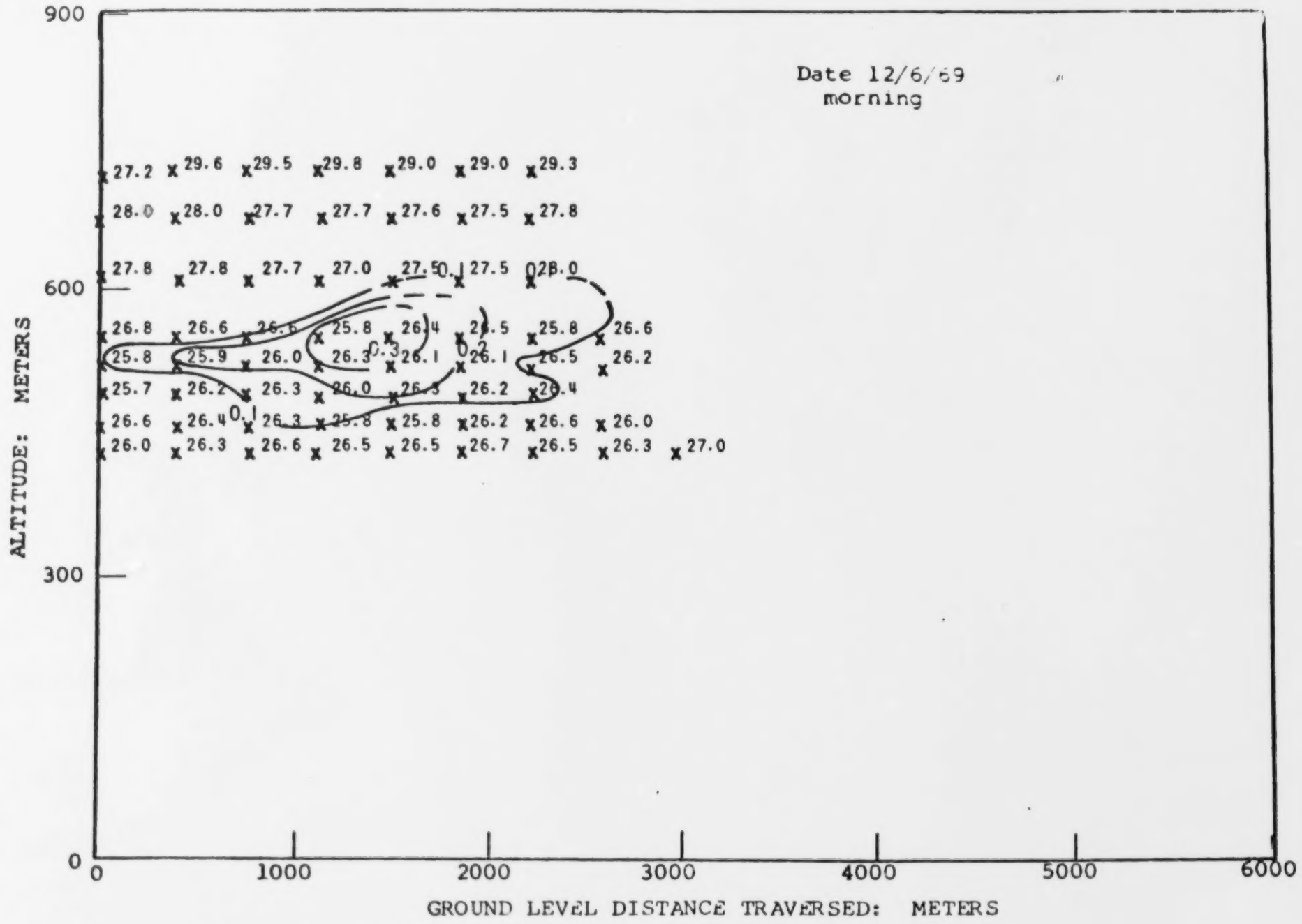


Figure 8: Sulfur Dioxide (ppm) Profile
at 640 Meters Downwind of Tower

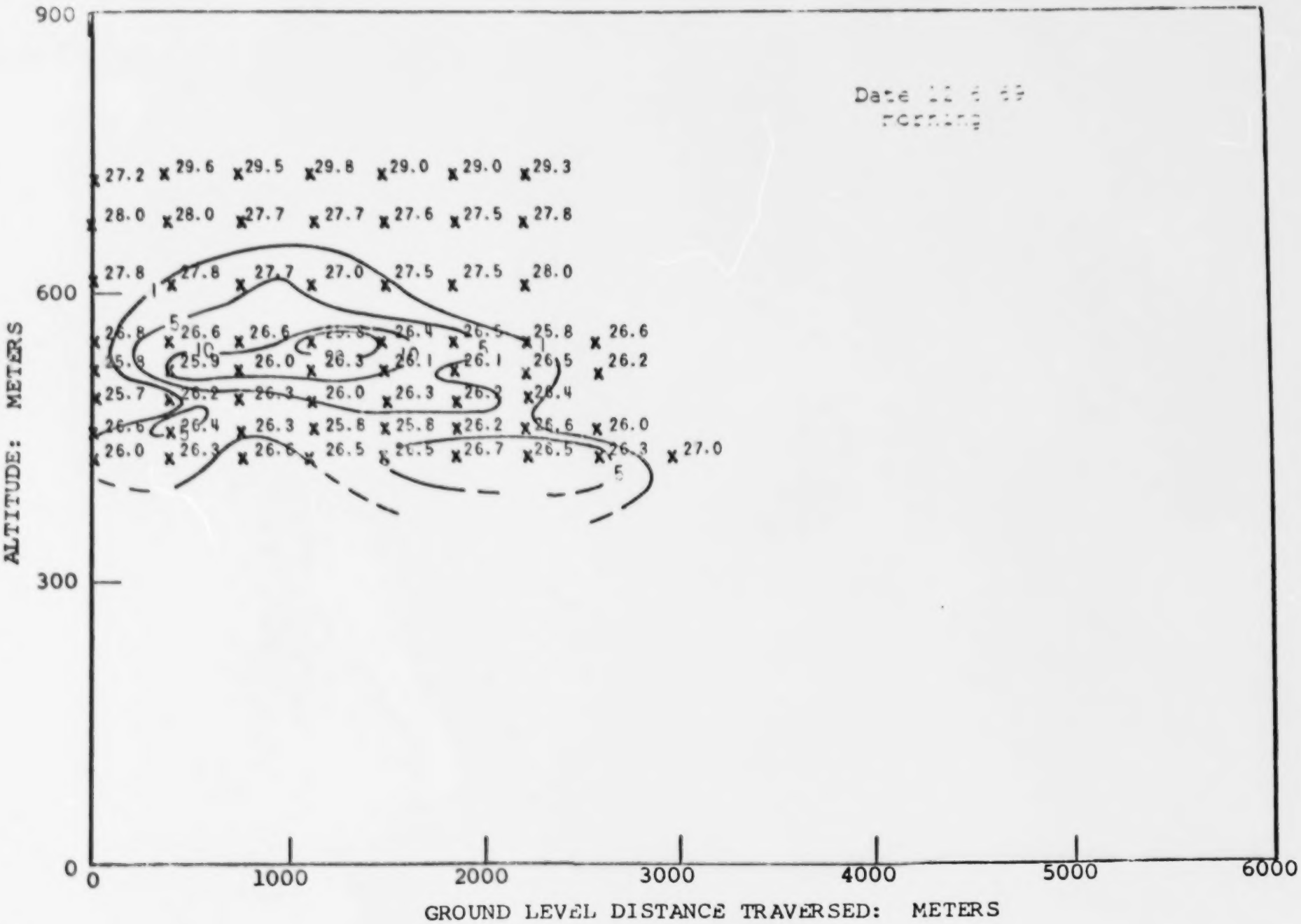


Figure 9: Relative Humidity Profile (% points above background at 640 Meters Downwind of Tower.

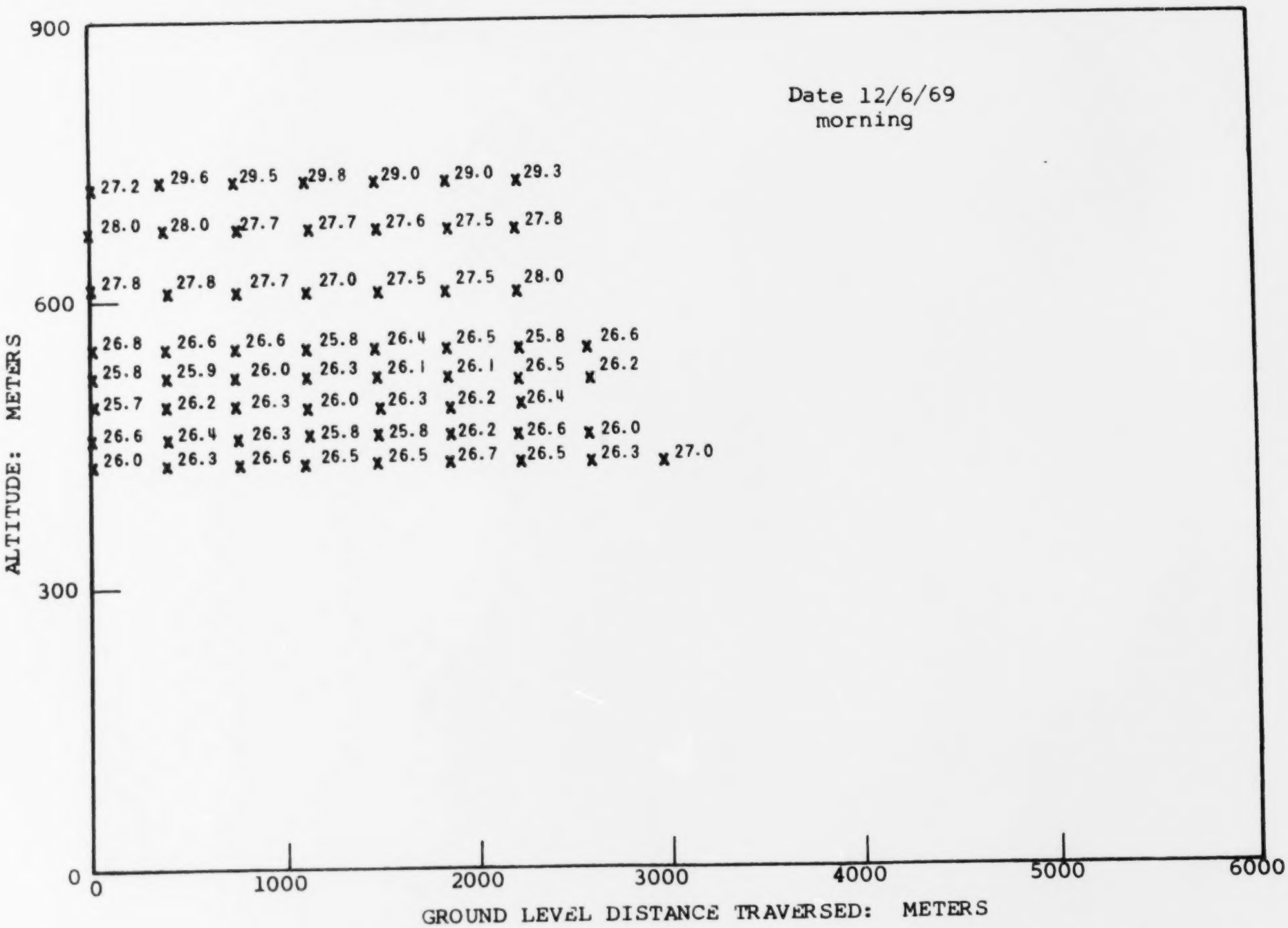


Figure 10: Temperature Profile (°F) at 640 Meters Downwind of Tower.

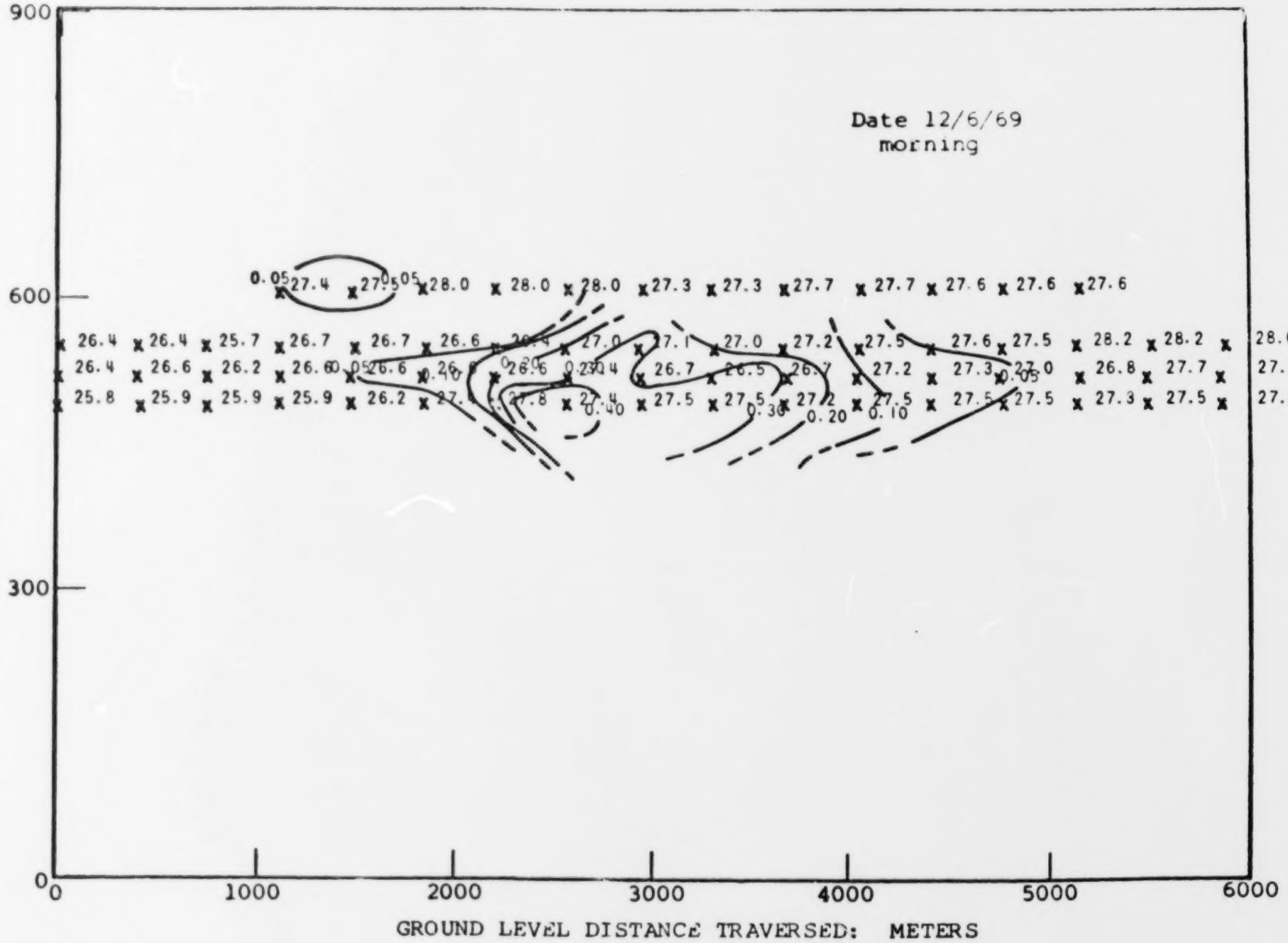


Figure 11: Sulfur Dioxide (ppm) Profile
at 4800 Meters Downwind of Tower

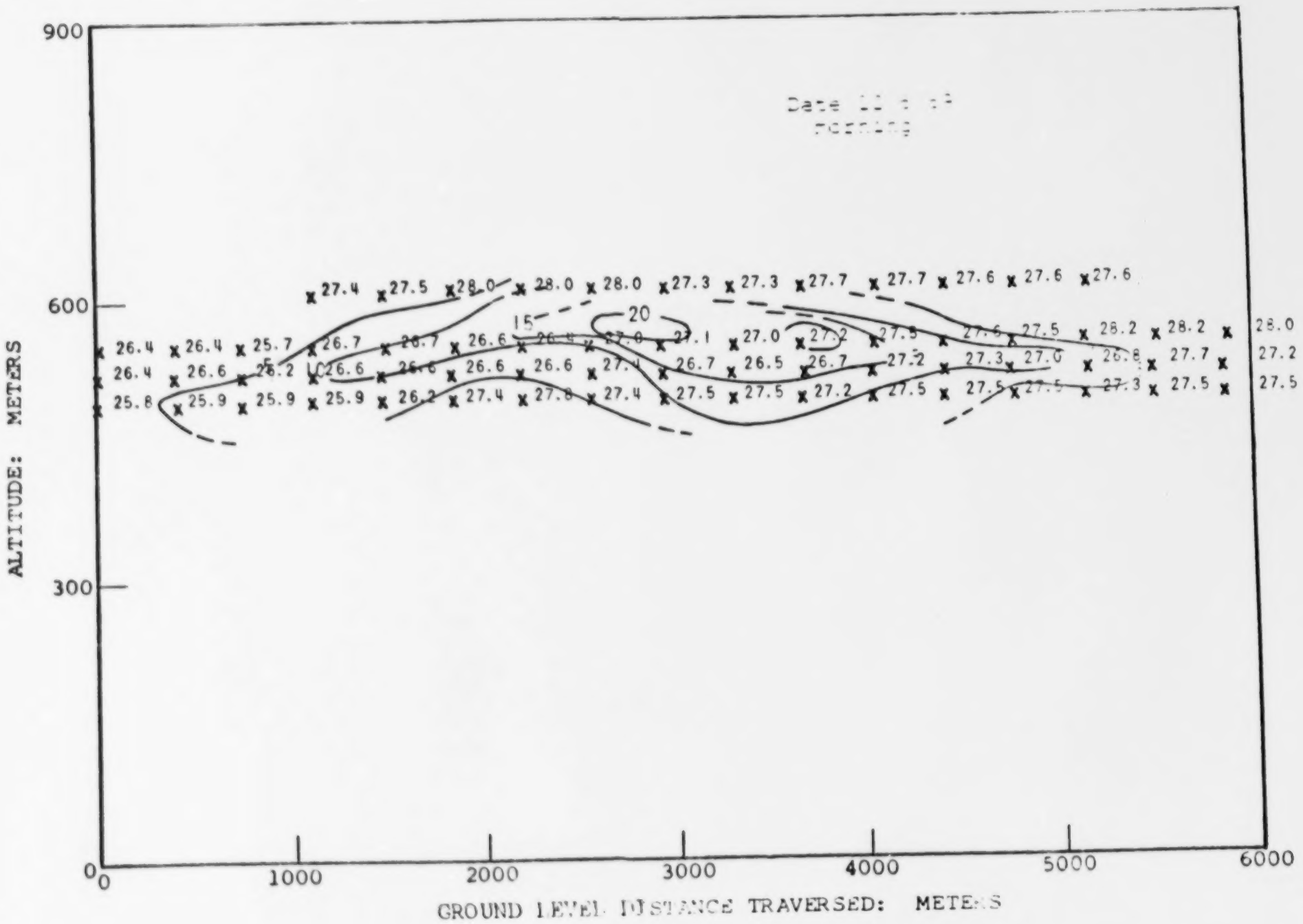


Figure 12: Relative Humidity [illegible] points above background at 4800 Meters Downwind of Tower.

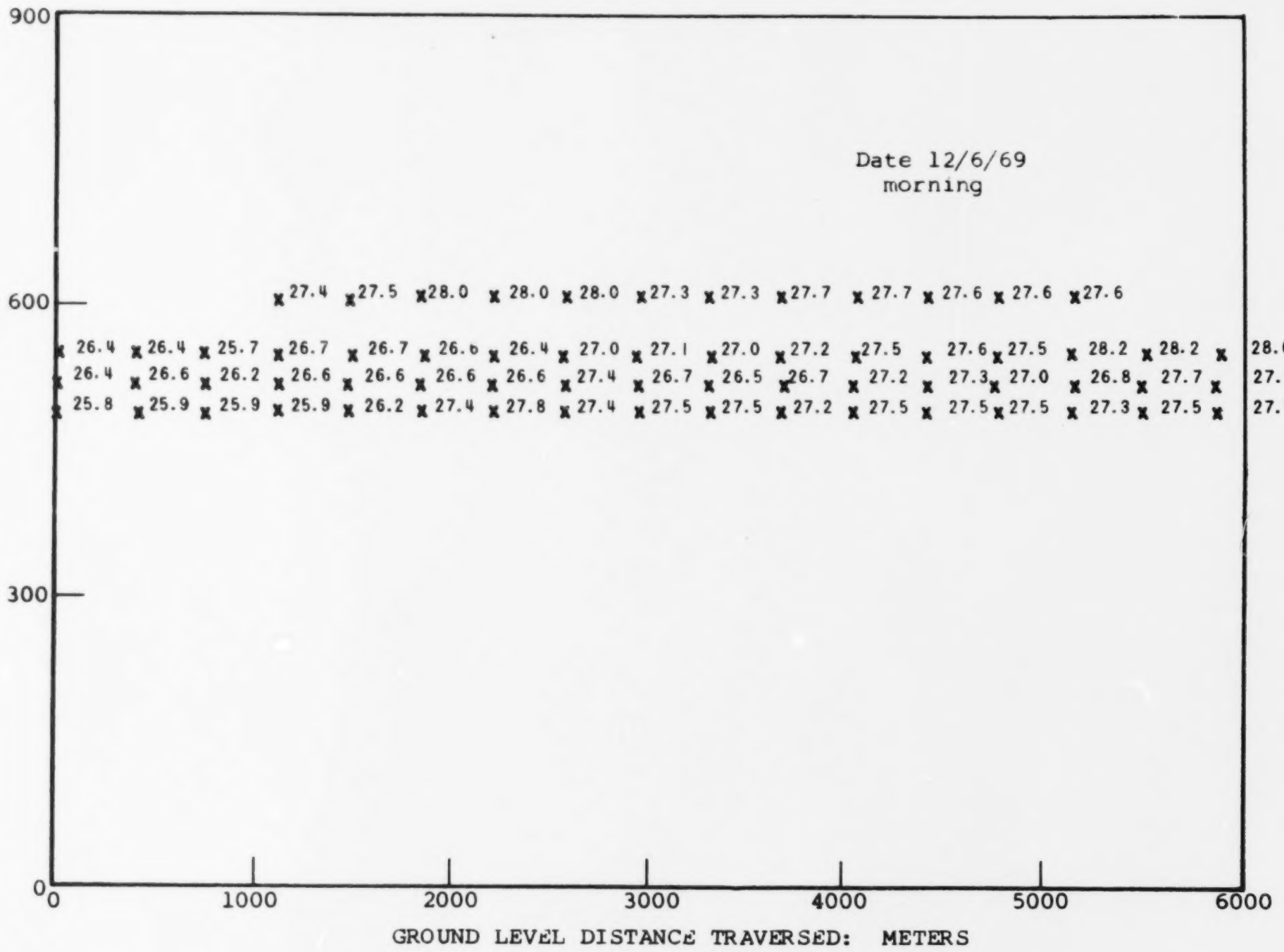


Figure 13: Temperature Profile (°F) at 4800 Meters Downwind of Tower.

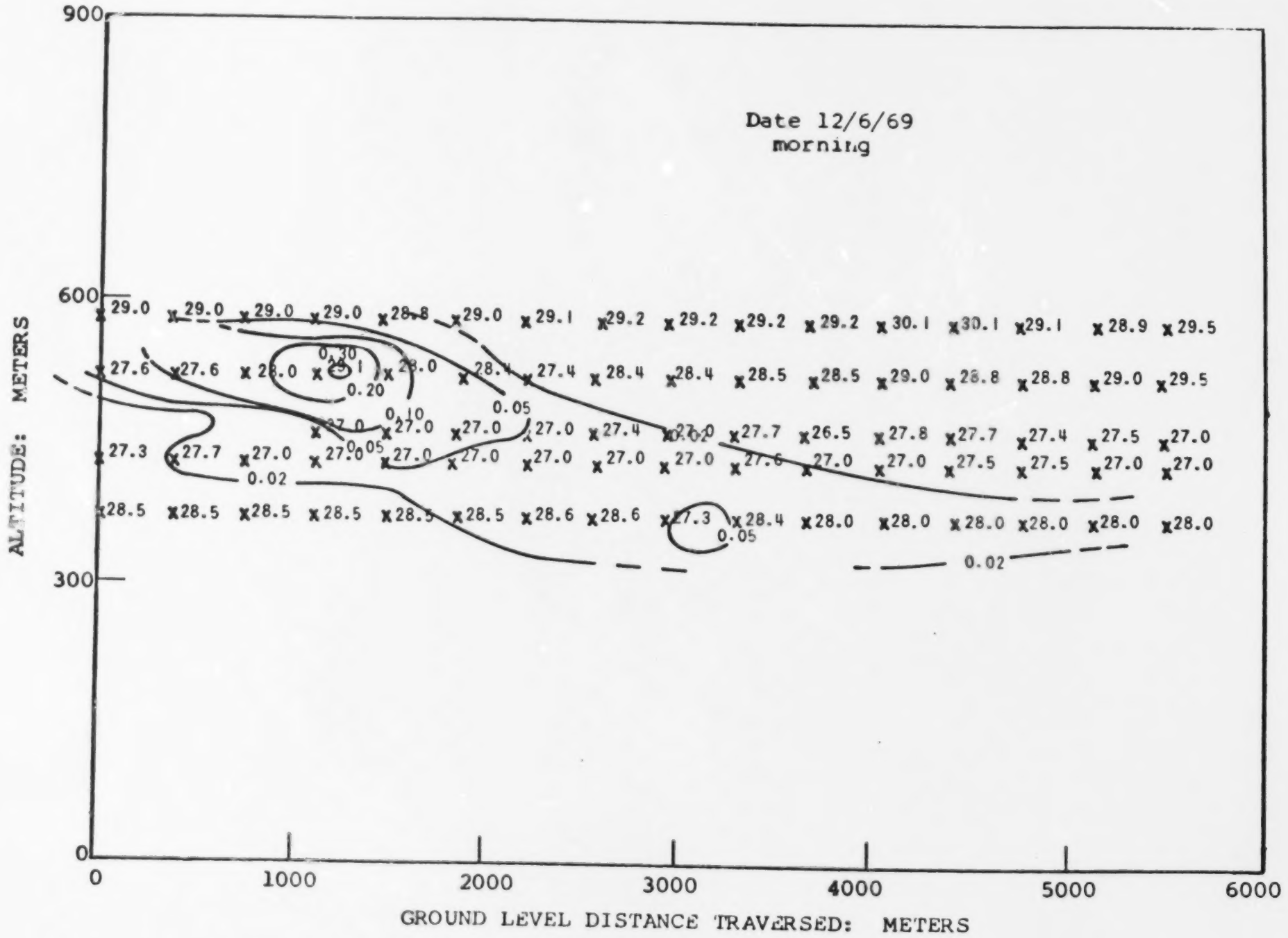


Figure 14: Sulfur Dioxide (ppm) Profile
at 10,800 Meters Downwind of Tower.

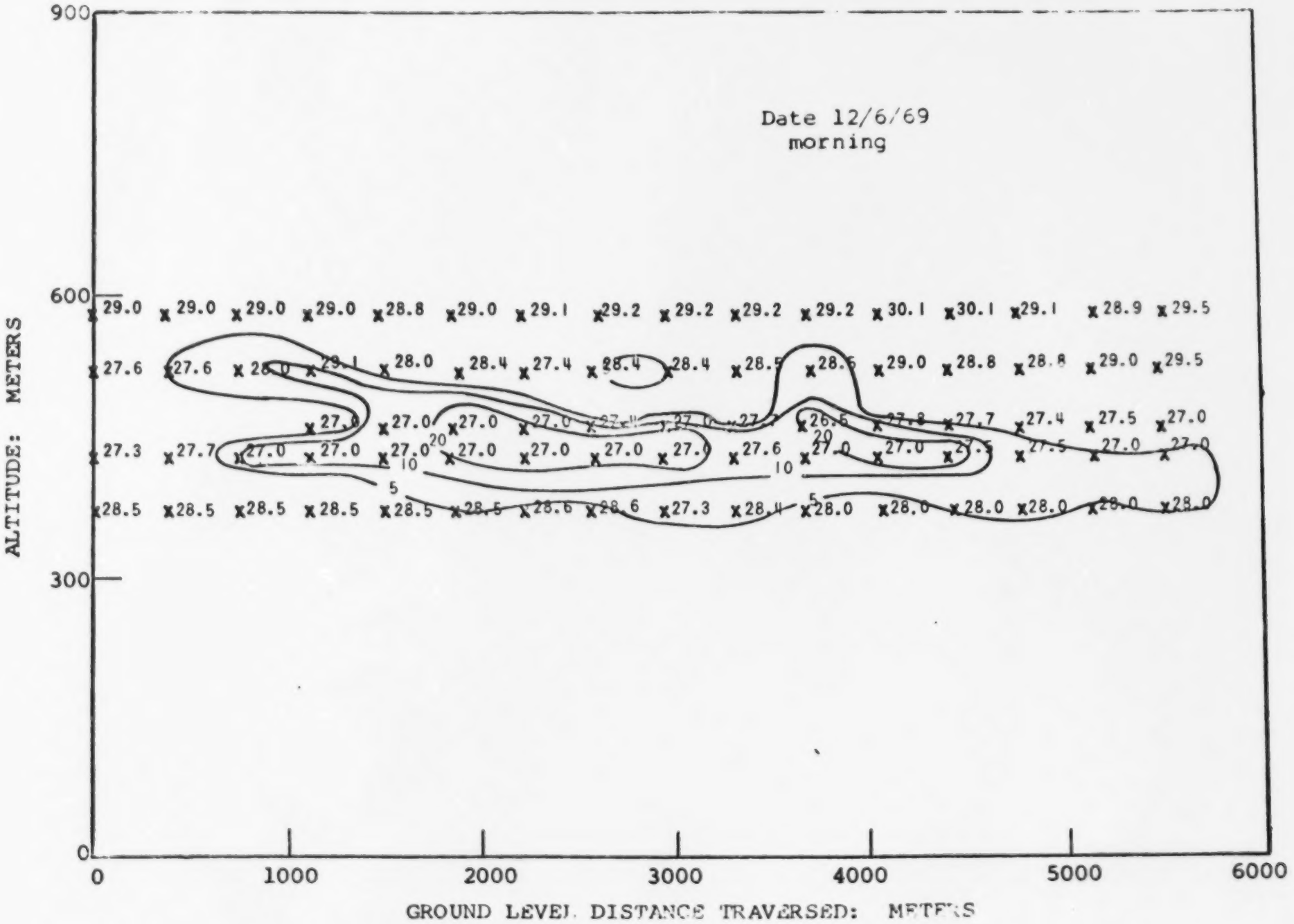


Figure 15: [illegible] Humidity Profile (% points above background) at 10,000 Meters Downwind of Tower

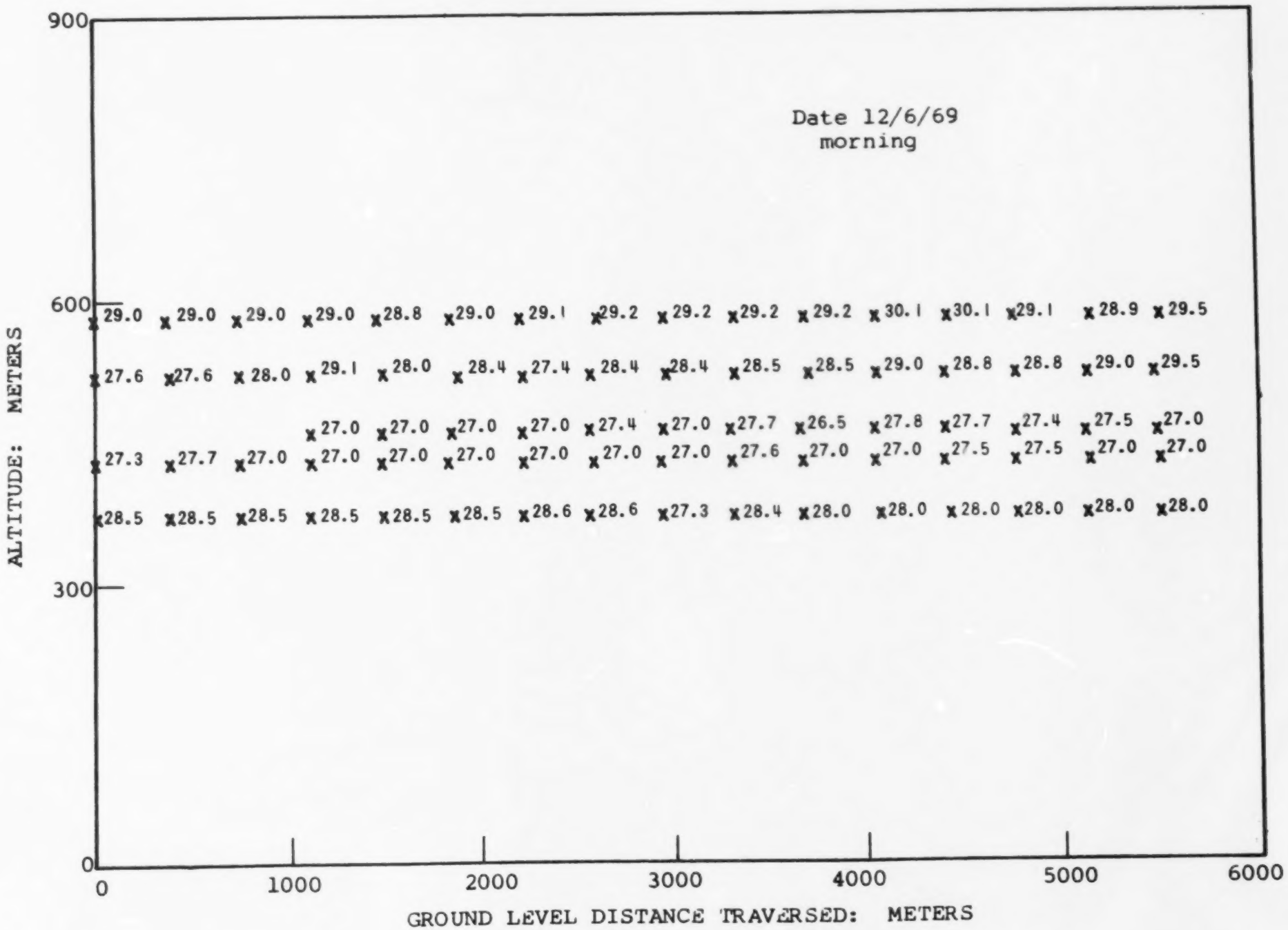


Figure 16: Temperature Profile (°F) at 10,800 Meters Downwind of Tower.

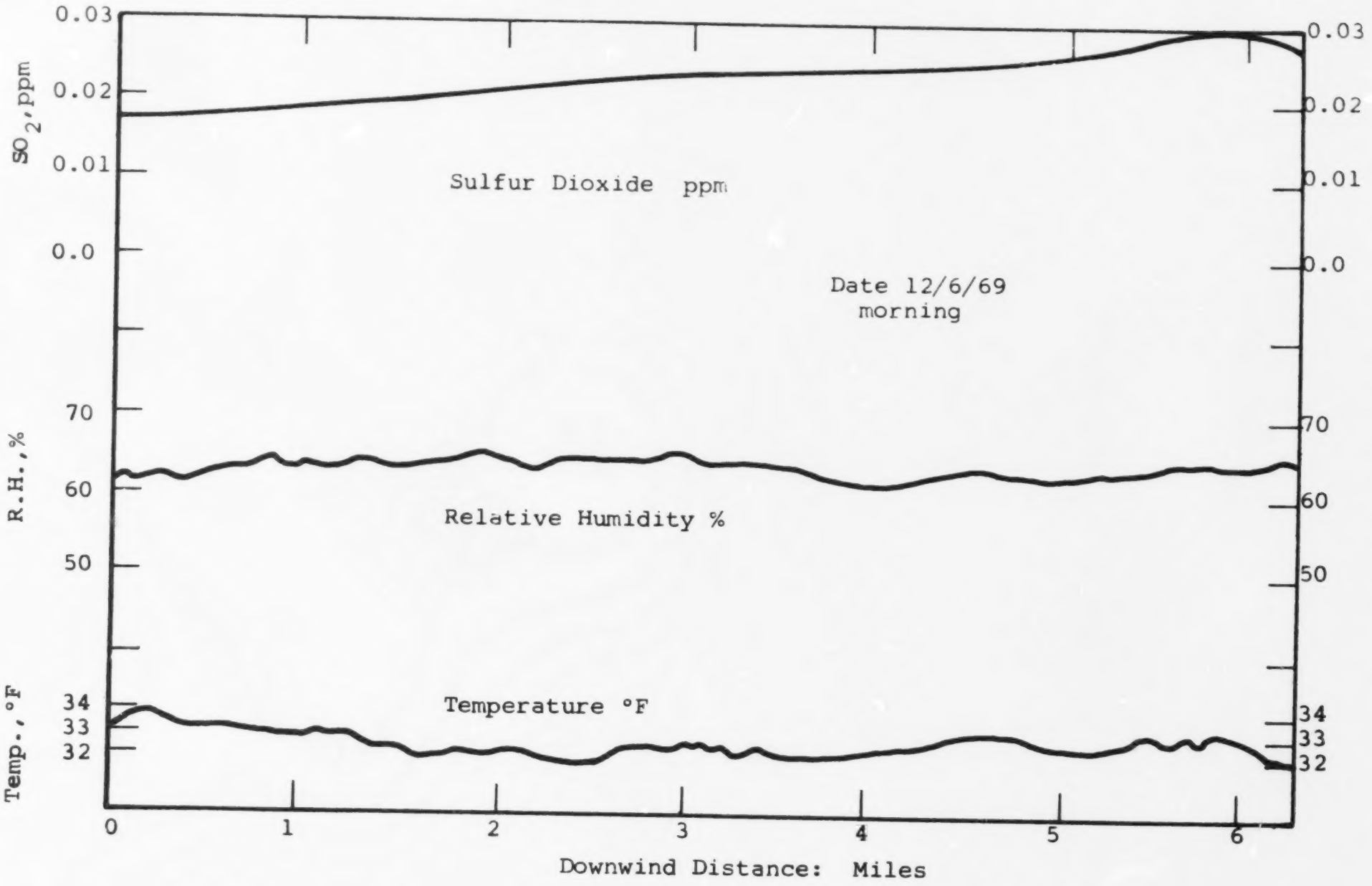


Figure 17: Ground Level Traverses Beneath Plume.

as horizontal expansion of the plume. The profiles for relative humidity data showed tower plumes at two altitudes; two stack plumes were also indicated by the sulfur dioxide profiles. Evaporation and heat release data for this date, Table A-3, indicate Unit #1 was generating 803 MW/hr of electricity while Unit #2 was generating only 535 MW/hr. This difference in generating capacity would cause the discharge from the cooling towers serving Unit #1 to have greater buoyancy and thus reach a greater altitude. The tower plumes rose from about 300 and 500 meters at a downwind distance of 2090 meters to 545 and 775 meters at a distance of 9960 meters.

A mathematical model was developed to explain the oscillation of the plume once it became nearly horizontal. The model covers both the visible and invisible portions of the plume and is derived in Appendix D. It is an adaptation of a simple cylindrical thermal model rising in a neutral atmosphere; such a model has been previously applied to bent-over plumes. For application to Keystone, the model was extended to include the latent heat of evaporation and condensation. For the rising plume from the tower, the equations of motion given by Morton (Reference 2) were used. This type of model is an entrainment model in which the admixture of ambient air into the plume takes place by turbulence induced by the plume motion. The results show the effect of buoyance removed or created by the evaporation or condensation of liquid water.

The data in Table 5 were used in the model and to obtain the dispersion pattern of the plume with distance downwind of the tower. Three cases of initial water content were treated, Table 6; the results are plotted in Figure 18. The model indicates that the plume will reach the ground when the moisture content is 70% in excess of saturation. The plume pattern for Case 2, plume moisture content 50% in excess of saturation, best fitted the observed motion of plume on the afternoon of December 6, 1969.

Table 5

PLUME AND ATMOSPHERIC CONDITIONS USED IN DISPERSION MODEL

Condition	Value
Tower air flow	8050 meter^3/sec
Tower diameter	61.3 meters
Tower height	99 meters
Tower air temperature	59°F
Relative humidity of exit air	100%
Atmospheric temperature	38°F
Potential temperature gradient	9.73×10^{-4}°F/meter
Atmospheric relative humidity	40%
Wind speed	3.7 meters/sec

Table 6

PLUME MOISTURE CONTENTS USED IN DISPERSION MODEL

	Case		
	1	2	3
Total Mass Fraction of Water (liquid plus vapor)	0.0140	0.0162	0.0183
Mass Fraction of Liquid Water	0.0032	0.0054	0.0075
Mass Fraction of Water Vapor(1)	0.0108	0.0108	0.0108

(1) Saturated air at 59°F.

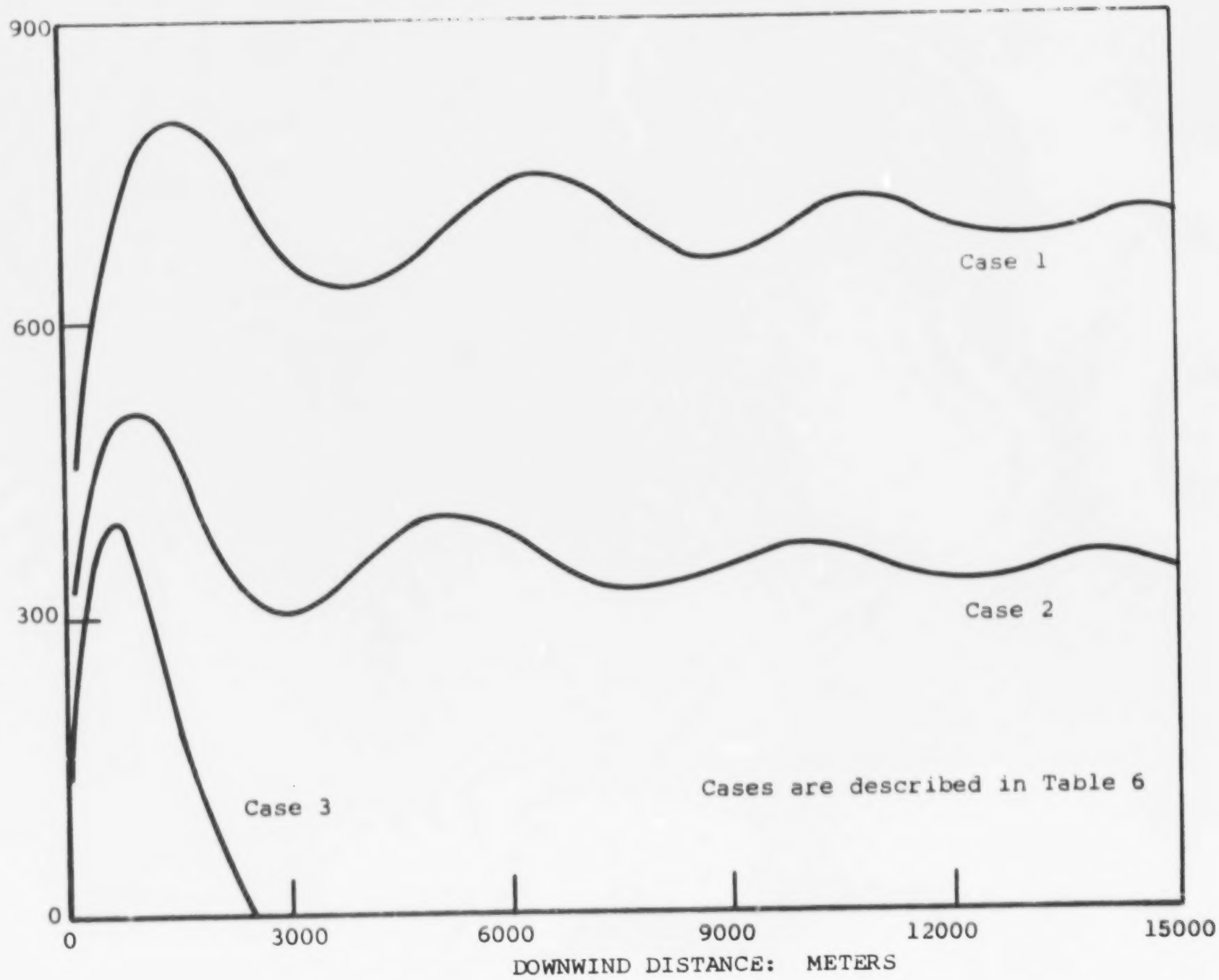


Figure 18: Effect of Plume Initial Moisture on Plume Behavior.

The presence of moisture in the plume over and above that necessary to saturate the exit air was not anticipated prior to the study, and no assessment of the exit air at the tower was planned. However, while measuring the inlet water temperature at the distributors within the tower, a dense water fog was invariably present. Penetration of a light beam from a flash light was on the order of a meter. Estimates of the distance light would penetrate through a fog, containing a mass fraction of liquid water of 0.54% as a function of droplet size, were made using the equation:

$$\frac{I}{I_o} = t = e^{-K\pi r^2 NL}$$

where

t = the fraction of incident light transmitted through through the plume of depth, L

K = scattering coefficient for water droplets

r = droplet radius

N = droplet concentration.

The results, Table 7, indicate that the visibility restrictions observed within the tower support the plume model contention that the tower effluent has a liquid water content 50% in excess of saturation.

Table 7

DISTANCE LIGHT TRANSMITTED THROUGH A FOG
CONTAINING 0.54% MOLE FRACTION LIQUID WATER

Size of water droplet, μm	Path Length, L, Meters	
	50% Transmission	10% Transmission
5	0.19	0.64
10	0.38	1.30
25	0.95	3.20
50	1.90	6.40
75	2.90	9.60

MIXING OF THE TOWER AND STACK PLUMES

The humid plumes from the cooling towers become mixed with the discharges from the power station stacks at downwind distances ranging from 200 to 1000 meters. The plumes from the two sources remained mixed at downwind distances of 11 270 meters, the farthest point at which aerial traverses were made. While the cooling tower plume was visible, normally 200 to 300 meters, the mixing was visually observed. After evaporation of the cooling tower plumes mixing was confirmed by the aerial sampling of the humidity and sulfur dioxide content of the atmosphere. Figures 8, 9, 11, 12, 14, 15, B-5, B-6, B-8, B-9, B-13, B-14, B-16, B-17, B-19, and B-20.

The mixing of plumes, while the cooling tower plumes were visible, was further shown by the presence of acid droplets and fly ash particles found in the cascade impactor samples, Appendix C. Because the cooling tower water supplies were neutralized, the presence of acid droplets in the plume is a priori evidence that sulfur dioxide from the stack gases had reacted with the moisture in the cooling tower plume. Most of the droplets were collected on the first stage of the cascade impactor and, therefore, exceed 11 μm in size. Since the collections were mainly on one stage it was not possible to obtain a droplet size distribution based on the aerodynamic collection efficiency of the collector. In Appendix C size distribution of the residue rings left after evaporation of the collected droplets are reported, but the residue size was not correlated to droplet size. While a relationship apparently exists between the humidity of the air and the ratio of acid to neutral droplets, Figure 19, no relationship was found between the sulfur dioxide content and the presence of acid droplets.

Almost without exception, the plume droplets, both acid and neutral, contained a large number of solid particles. Usually these particles were small - less than a few microns in

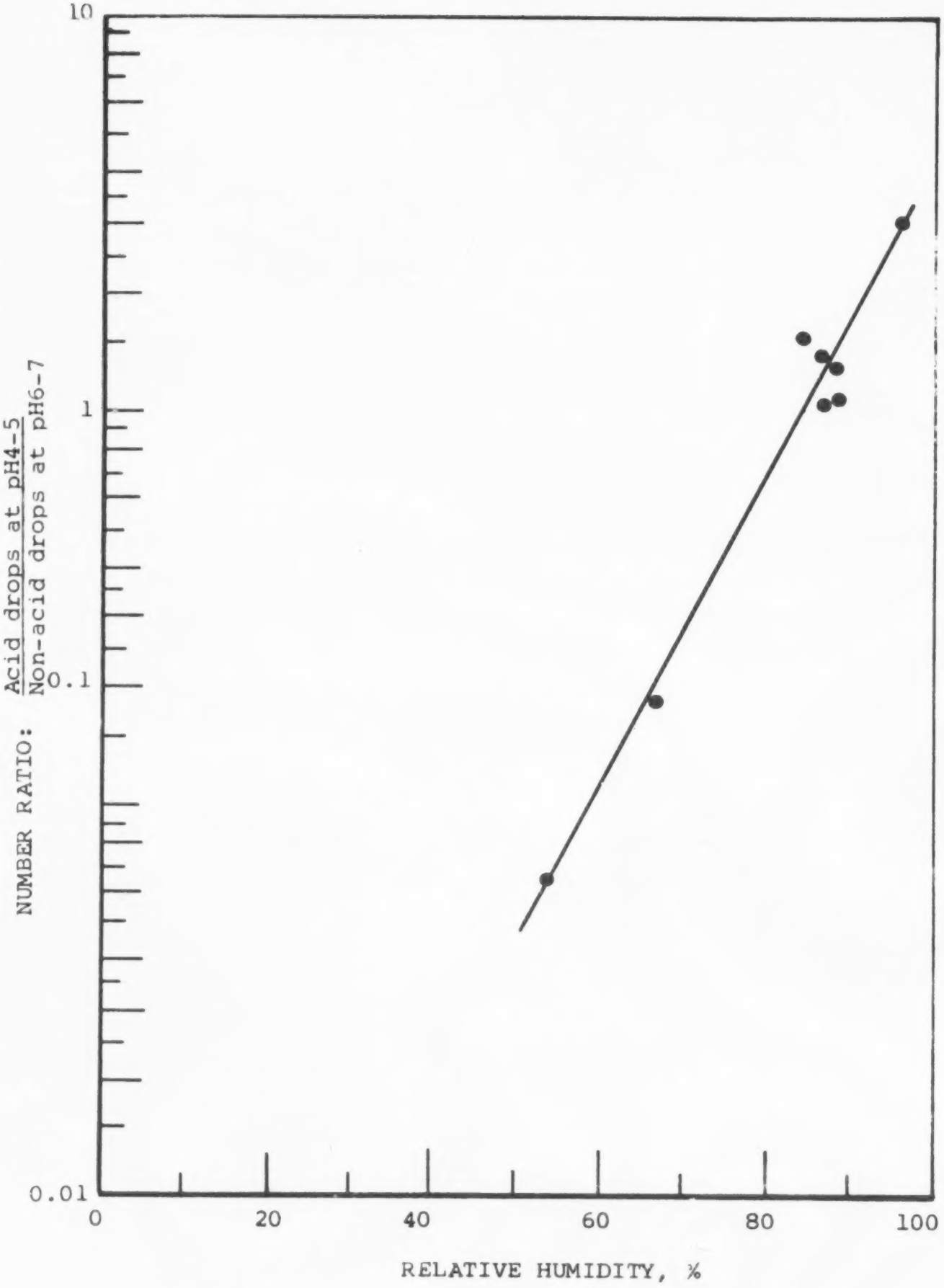


Figure 19: Variation of Acid Drop Concentration with Humidity.

size. However, on occasion particles up to a few hundred microns in size were sampled. The particles were presumed to be fly ash.

The mixing of the plume can produce significant changes in the composition of the power station emissions. It is known that humidity enhances the oxidation of sulfur dioxide and the formation of sulfuric acid. The presence of particulate matter can promote condensation and provide heat-sinks for chemical reactions.

When the two units of the power station were operating at greatly different capacities, as they were on December 2, 1969, two distinct stack plumes were discernible from the sulfur dioxide profiles at downwind distances up to 9960 meters, Figures B-5 and B-8. Plume spreading was much greater in a horizontal direction than in the vertical direction.

The degree of mixedness between the plumes cannot be stated precisely. The plumes occupy the same space; and the visible humid plume is highly turbulent, as determined by its action on the aircraft. However, the lack of a correlation between the acid droplets and sulfur dioxide concentration suggests the plumes are not uniformly mixed and may be just comingled. Also, it is obvious that the altitude reached by the plumes is dependent upon their buoyancy; and a critical factor in determining buoyancy is the operating capacity of the plant. From the profiles obtained, it was apparent that the discharges from the 244-meter stacks comingled with the humid plume effluent from 99-meter towers. The two heights apparently balance out the differences in plume buoyancy. This may represent a deficiency in station design if mixing of the stack and tower plumes is undesirable.

POSSIBLE LOCAL EFFECTS OF HEAT AND WATER VAPOR RELEASE

Cooling towers have the potential to inadvertently modify the weather surrounding their location. The weather effects that could be modified are fog, rain, drizzle, and cloud initiation. Any modification would be the result of the release of large quantities of heat and water vapor into the atmosphere from the towers.

Local fogging and the creation of road hazards due to icing and visibility restriction are a well documented (Reference 3) nuisance associated with forced draft cooling towers. Natural draft towers present a much larger point emission source of water vapor than forced draft towers and have lower exit velocities (~3.7 meters/second). However, they also have a greater heat content and are discharged from much greater heights. At Keystone, no increase in ground level humidity was detected by the low level helicoper traverses.

It was observed that the Keystone towers do not produce drizzle precipitation in the immediate vicinity of the towers. No droplets were detected by sensitized (Ozalid) paper swatches laid out beneath the Keystone towers.

Juxtapositioning of cooling towers emitting heat and water vapor provides circumstances favorable to the formation of convective cells under certain climatic conditions. On occasion the Keystone plumes were witnessed to evaporate and then recondense at higher altitudes further downwind. Under stable temperature conditions and high ambient air humidities, the Keystone plume persisted and merged downwind with the existing stratus cloud cover. Initiation of cumulus clouds during periods of otherwise clear skies was observed at Keystone on one occasion by Mr. Frank Schiermeier of the Air Pollution Control Office, but the clouds triggered by the

cooling tower emissions only prededed natural cloud formation. On the basis of the available climatological data (Figure 4), there is no evidence that annual precipitation has been altered by the presence of the Keystone station. Only in July 1969, is there a possibility of rainfall enhancement downwind of Keystone (Figure 6).

CONCLUSIONS

Natural draft cooling towers are being selected with increasing frequency as a means of disposing of large quantities of waste heat. The first natural draft tower in the United States went on stream on 1962. Currently, there are 18 operational towers; projections indicate that between 32 and 40 will be operational by 1974. These towers will be located predominantly in the Northern Appalachian areas; 22 will be in Pennsylvania. Without exception, the natural draft cooling towers are associated with electrical utilities. They are being used despite an unfavorable relationship between their cooling capacity and the demand for power.

Natural draft towers vent large quantities of heat and water vapor to the atmosphere. At Keystone approximately 10,000 gal/min of water are evaporated, and 120 million BTU/min of heat are released when the station is operating at 80 to 86% of its rated 1800-megawatt capacity. While under observation during this study, the visible portion of the tower plume normally rose to an altitude of less than 200 meters and traveled downwind about 200 meters before evaporating. However, the dimensions of the visible portion of the plume are greatly dependent on the temperature and humidity of the ambient air. When temperatures are 25-30°F and the relative humidity is high, the plume can be seen for thousands of meters. Even when the plume was visible over only a short distance, its path could be traced up to 11,000 meters by aerial measurements of humidity. An entrainment model indicated that plume moisture content 50% in excess of saturation at the lower exit would produce the observed plume pattern.

The cooling tower plume comingles with the effluent from the power station stacks. The mixing of the plumes from the two sources takes place between 200 and 1000 meters downwind

of the station; the plumes remain mixed for distances up to 11,200 meters, the farthest downwind point at which aerial samples were taken. Mixing of the plumes was confirmed by the presence of acid droplets and fly ash particles in the visible portion of the cooling tower plume. When the two power-generating units at Keystone were operating at different rates, the effluents from the units reached different altitudes. It appears, though, that the tower and stack plumes serving a generating unit have similar total buoyancies since they reach the same altitude.

While under observation during this study, no adverse weather effects due to the operation of the Keystone Station could be shown conclusively. Drizzle beneath the tower from water droplet carry-over was not detected, and no increase in ground level humidity underneath the plume path was observed. Only in July 1969 was there a possibility of precipitation enhancement according to existing local Weather Bureau climatogical records. At all other times the monthly precipitation totals during the period since Keystone was placed in operation were within the envelope of natural variation for the area. Cloud initiation is infrequent, but the merging of the plume with the stratus cloud cover is relatively common.

The full environmental effects of natural draft cooling towers cannot be stated conclusively from the study for three reasons. The station effluents were observed and sampled over a short time period that represented only one season; the station was operated at 1/6 capacity during a portion of the field tests; and field instrumentation was lacking in several essential areas.

RECOMMENDATIONS

Recommendations to further the study of the effects of natural draft cooling towers serving Keystone are suggested in three areas. First, the station should be instrumented to obtain reliable water balance and heat loss data. The nature of the water losses from the towers should be determined. The British Standard (BS 4485, 1969) should be reviewed to determine its application to American use. Visual observations of the plume at Keystone should become part of the daily station log.

Secondly, the present network of weather stations should be expanded and upgraded. At least one, and ideally two, stations should be added in the easterly quadrant, 8000 meters from Keystone. Another station should be placed similarly east to east northeast of Homer City. Observations at cooperative non-recording rain gauge stations should be extended to include such elements as fog occurrence, thunderstorms, precipitation days, and relative humidity and dew point data. The facilities at the Jimmy Stewart Airport should be expanded to read these elements. Siting of a weather radar station in the area to study precipitation patterns over a period of several years would help to answer questions concerning the weather effects produced by the towers.

Thirdly, if the mixing of cooling tower plumes and station effluent is undesirable, the factors affecting plume buoyancy should be studied. The design at Keystone apparently imparts to the two effluents the same total buoyancy, despite differences in heights of the towers and stacks.

REFERENCES

1. "Monthly Weather Review" U.S. Dept. of Commerce, Environmental Science Services Administration, Vols. 96 and 97.

2. Morton, B. R. "Buoyant Plumes in a Moist Atmosphere" J. Fluid Mechanics 2, 1957.

3. Hall, W. A. "Elimination of Cooling Tower Fog from a Highway" Air Pollution Control Assoc. J 12, p. 379, 1962.

Appendix A

Keystone: Site, Climatology, Tower Operation

Keystone: Site, Climatology, Tower Operation

Keystone is an 1800-megawatt, mine mouth, coal-fired electrical power generating station having two identical 900-megawatt units. Associated with each unit is a 244-meter chimney stack and two 99-meter natural draft cooling towers. A photograph of the station is shown in Figure A-1. The first unit went on stream in 1967 and the second unit in 1968. Keystone is operated by Pennelec on behalf of a consortium of owners. The electric power produced is transmitted primarily to the Northeastern Atlantic States.

Keystone is located near Shelocta, Indiana County, Pennsylvania. Similar generating stations are located at nearby Homer City and Johnstown, Pennsylvania. A map of the area surrounding Keystone is shown in Figure 3. The area is rural and hilly. Jimmy Stewart Airport at Indiana provides a convenient operational base for aerial surveys of the Keystone plumes and source of local meteorological data.

The area surrounding Keystone has relatively high precipitation levels, about 890 to 1016 mm/yr. The precipitation is distributed evenly throughout the year. Snowfall during the winter averages around 1270 to 1530 mm/yr. There is a 50% chance of measurable precipitation on any date. Thunderstorms normally occur during all seasons except mid-winter; thunderstorms are most frequent in mid-summer. Temperature inversions occur frequently between altitudes of 152 to 305 meters; surface inversions also occur often. Cold air drainage induced by the

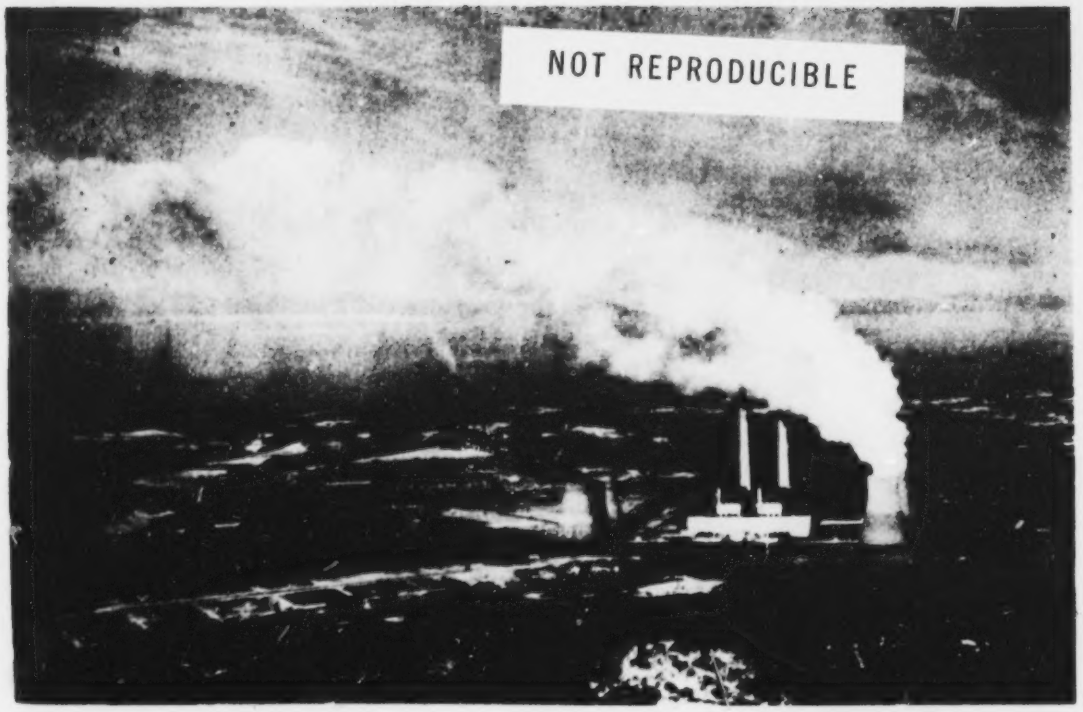


Figure A-1: Photograph of the Keystone Power Station.

many hills leads to the formation of early morning fog. Fog can be presistent in the river valleys during the colder months. Wind speed averages between 8 to 10 mph and is predominantly from the west southwest.

Natural draft cooling towers dissipate the waste heat at Keystone. Two cooling towers serve each power generating unit. The four towers at Keystone represent the most concentrated number of natural draft towers at any one site in the United States. The Keystone towers have the typical hyperbolic shape and are 99 meters in height. They were designed and built by Research-Cottrell, operate with counter-current flow,and have a total cooling capacity of 560,000 gpm. Makeup water to balance water evaporation and other losses is obtained from Plum Creek. The flow in this creek is controlled by an up-stream reservoir. The reservoir permits the extraction of makeup water from the creek during draught periods without damage to the creek. Figure A-2 is a water flow schematic for one of the 900-megawatt units. Sources of water addition to the system are the makeup pumps (MUP) and sources of water loss; in addition to tower evaporation, are the service water pump (SWP), ash handling pumps (AP), diesel fire suction pump, and blowdown. Only the service water pumps operate continuously.

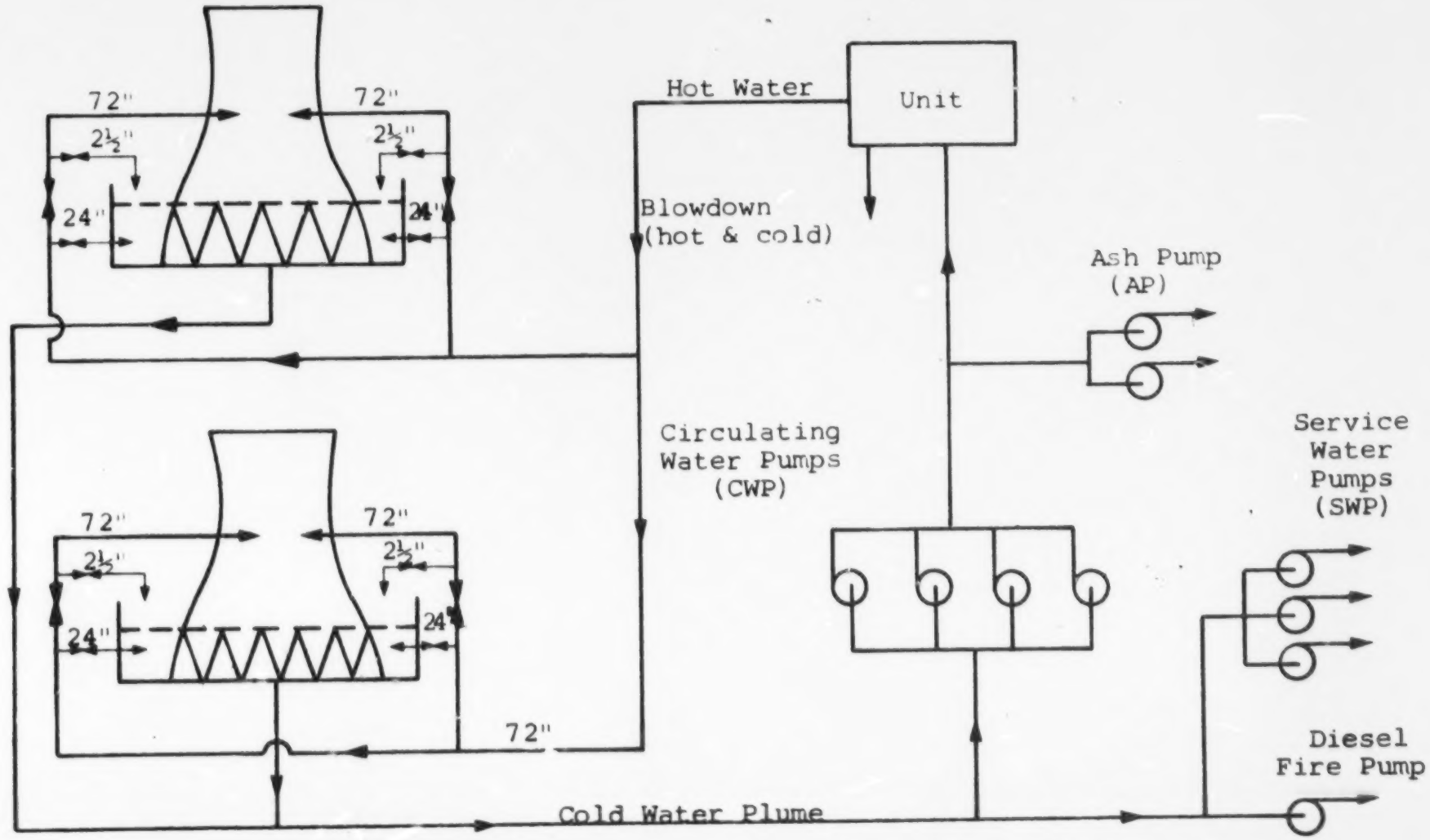
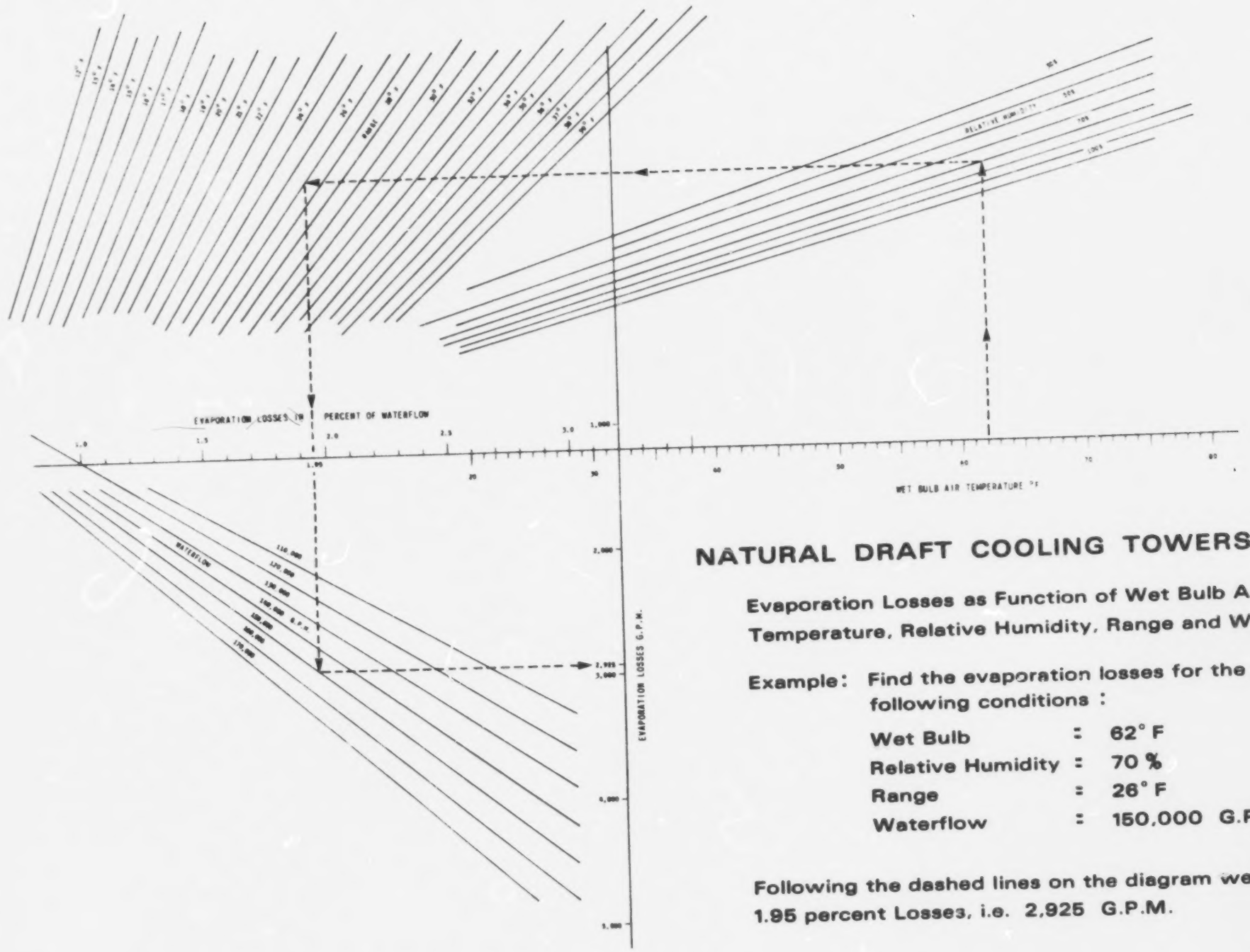


Figure A-2: Cooling Water Schematic for Keystone Station.

The determination of water and heat released by the cooling towers was hampered by the lack of suitable equipment and an accepted test technique. Only after this study was completed was British Standard 4485 (1969) available. The method used during this study to evaluate the cooling towers was to measure essential temperatures and pumping pressures throughout the system and determine the evaporation loss from the monograph supplied by Research-Cottrell, Figure A-3. The heat released by the towers was then calculated. Pumping pressures were used to obtain water flows from pump characteristic curves supplied by the suppliers of the pumps. Table A-1 shows the pressures and water flows for the CWP, SWP, and MUP pumps. Data for the ash pumps were not available. It was found that some pressure gauges were reading erroneously; consequently, some water flows were estimated. As a result, the water flow data reported is only a reasonable estimate.



NATURAL DRAFT COOLING TOWERS

Evaporation Losses as Function of Wet Bulb Air Temperature, Relative Humidity, Range and Waterflow

Example: Find the evaporation losses for the following conditions :

Wet Bulb	:	62° F
Relative Humidity	:	70 %
Range	:	26° F
Waterflow	:	150,000 G.P.M.

Following the dashed lines on the diagram we find 1.95 percent Losses, i.e. 2,925 G.P.M.

Figure A-3: Evaporation Losses From Cooling Tower.

Table A-1

Pumping Pressures and Water Flows at Keystone

Date	Local Time	Pumping Head, psig: UNIT # 1 CWP A	CWP B	CWP C	CWP D	SWP(2) A	SWP B	SWP C	UNIT # 2 CWP A	CWP B	CWP C	CWP D	SWP A	SWP B	SWP C	UNITS=1&2 MUP A	MUP B(3)	MUP C	Water Flows, Thousands of gallons per minute: Cooling Water(1) Unit=1	Cooling Water(1) Unit=2	Service Water(2) Unit=1	Service Water Unit=2	Make-up Water Units=1&2
9/19/69	1555	29.2	32.0	s(4)	30.0	178	178	178	s	30.0	31.0	35.5	95	95	95	-	-	-	253.5	243.3	-	14.25	-
9/20/69	1100	30.7	33.0	s	33.5	179	179	179	s	29.7	31.3	35.5	95	95	95	44	58	41	243.0	243.3	-	14.25	31.5
9/20/69	1515	30.7	34.0	s	33.5	184	184	184	s	29.0	29.2	35.5	90	90	90	45	57	41	240.6	253.5	-	16.50	31.1
9/21/69	0900	30.7	34.0	s	33.5	178	178	178	s	29.1	31.7	36.6	102	102	102	48	61	44	240.8	243.0	-	12.00	28.6
9/21/69	1500	30.7	34.0	s	34.0	190	190	190	s	31.0	31.5	36.0	100	100	100	47	59	43	238.5	243.0	-	12.24	29.5
9/22/69	1015	30.7	33.5	s	34.0	177	177	177	s	30.5	30.4	36.0	107	107	107	46	59	43	240.7	243.5	-	9.84	30.1
9/22/69	1405	30.7	33.8	s	33.5	177	177	177	s	32.0	31.5	35.8	94	94	94	45	56	.0	240.3	240.0	-	14.70	31.6
9/23/69	1030	30.7	33.7	s	33.5	178	178	178	s	31.0	31.1	36.0	95	95	95	46	55	43	240.5	240.6	-	14.25	30.1
9/23/69	1545	30.7	33.8	s	33.5	178	178	178	s	31.6	31.1	36.0	98	98	98	46	58	40	240.6	240.9	-	13.20	30.9
9/24/69	0850	30.7	34.0	s	33.3	182	182	182	s	31.0	31.7	35.5	89	89	89	44	56	41	240.5	240.6	-	16.80	31.5
9/24/69	1040	30.7	33.9	s	33.4	180	180	180	s	32.0	31.5	35.8	93	93	93	45	57	42	240.6	240.0	-	15.30	30.8
9/24/69	1340	30.7	33.9	s	33.4	179	179	179	s	31.5	31.6	35.6	91	91	91	44	56	41	240.6	240.9	-	16.05	31.5
11/28/69	1525	31.2	32.9	30.6	s	-	-	-	31.0	30.5	s	32.3	-	-	-	-	-	-	248.5	243.7	-	-	-
11/29/69	1435	31.7	34.5	30.1	s	-	-	-	30.3	30.0	s	35.5	-	-	-	-	-	-	244.9	243.6	-	-	-
11/30/69	1053	35.2	34.5	30.1	s	-	-	-	29.7	30.2	s	36.5	-	-	-	-	-	-	238.5	244.0	-	-	-
12/2/69	0943	35.2	36.5	34.3	37.3	-	-	-	30.8	29.8	s	36.2	-	-	-	-	-	-	296.4	243.7	-	-	-
12/2/69	1430	39.7	38.0	34.4	37.4	-	-	-	30.8	29.8	s	36.2	-	-	-	-	-	-	281.5	241.9	-	-	-
12/5/69(5)	0935	-	-	-	-	-	-	-	s	39.9	33.8	37.5	-	-	-	-	-	-	-	231.6	-	-	-
12/6/69(5)	0830	-	-	-	-	-	-	-	s	30.3	31.4	36.1	-	-	-	-	-	-	-	242.3	-	-	-
12/6/69(5)	1525	-	-	-	-	-	-	-	s	31.6	31.9	36.5	-	-	-	-	-	-	-	238.0	-	-	-

(1) Cooling water flow for two towers per unit. Divide Flow in half to determine evaporation loss in Figure A-3.

(2) Pressure gauge in error, flow not calculated.

(3) Pressure gauge in error, flow estimated at 10,000 gpm.

(4) Standby, not operating.

(5) Unit #1 shut-down, not operating.

Table A-2 presents the essential temperature data in the Keystone cooling water system. The time required to gather all the temperature data was usually about 30 to 45 minutes. During this time some minor changes in the ambient air wet and dry bulb temperatures occurred. These changes did not affect materially the relative humidity of the air. Tower exit air temperatures were taken within the tower about 3 meters above the point of water distribution; the water distribution sprays system is located approximately 12 to 15 meters from the base of the towers. The data in Table A-2 were used to calculate the relative humidity of the ambient air and the cooling tower range, the tower range being the difference between the inlet and outlet water temperatures. Data on relative humidity, tower range, and water flow were used in Figure A-3 to find the evaporation loss. The amount of heat released was calculated from the evaporation loss. Heat released is reported in Table A-3. Also reported is an estimate of the electrical power being produced at the time the data were obtained.

Several alternate techniques to evaluate the cooling towers were examined. All proved unsatisfactory. The use of pitot tube to measure flow, while providing reliable data, was discarded because additional manpower would be needed, scaffolding would be required, and suitable equipment could not be made available. The use of pump motor power input data (amps) to calculate water flows gave data that was variable and suspect. Although the automatic data monitoring system at the Keystone station was

Table A-2

Essential Temperature Data at Keystone

Date	Local Time Start	Local Time Finish	Ambient Air, °F Wet Bulb Start	Wet Bulb Finish	Dry Bulb Start	Dry Bulb Finish	Water Temperature, °F Unit #1 Tower A Pond[1]	Tower A inlet	Tower A Make-up[2]	Unit #1 Tower B Pond[1]	Tower B inlet	Unit #2 Tower A Pond[1]	Tower A inlet	Unit #2 Tower B Pond[1]	Tower B inlet	Tower Exit Air Temperature, °F Unit #1 A	Unit #1 B	Unit #2 A	Unit #2 B
9/19/69	1555	1625	55.0	55.3	64.2	63.8	72.0	-	58.5	77.0	-	80.5	-	80.0	-	-	-	-	-
9/20/69	1100	1230	54.0	55.8	58.0	62.1	70.0	98.0	59.0	75.0	98.0	79.0	111.5	79.0	111.0	-	-	-	-
9/20/69	1515	1600	54.0	54.9	57.0	58.7	71.5	99.0	60.0	75.5	100.0	80.5	113.0	79.0	113.3	-	-	-	-
9/21/69	0900	0945	50.3	50.8	52.8	54.8	66.0	89.2	58.0	69.5	89.0	72.7	93.5	72.0	93.8	-	-	-	-
9/21/69	1500	1550	61.0	60.0	72.0	72.3	74.5	96.0	60.0	78.0	96.0	78.0	100.0	79.0	99.5	-	-	-	-
9/22/69	1015	1115	55.0	59.8	58.0	65.8	68.3	95.5	58.5	72.0	96.0	77.5	101.5	76.5	101.0	-	-	-	-
9/22/69	1405	1455	62.6	62.8	73.7	74.3	75.2	102.4	60.0	79.4	102.9	82.3	106.3	82.3	105.8	-	-	-	-
9/23/69	1030	1105	56.6	59.3	61.5	65.0	68.7	95.0	58.0	71.7	95.0	79.7	111.8	78.2	112.0	-	-	-	-
9/23/69	1545	1600	64.8	64.0	71.2	72.9	79.0	103.8	60.0	80.0	104.5	84.3	117.5	84.5	117.7	-	-	-	-
9/24/69	0850	0940	59.9	62.0	60.0	64.0	74.9	100.0	61.0	77.0	101.1	82.7	115.0	81.3	115.0	-	-	-	-
9/24/69	1040	1107	63.3	62.5	53.3	66.5	76.7	102.8	62.0	79.4	103.5	84.9	117.2	83.0	117.1	-	-	-	-
9/24/69	1340	1415	64.0	64.4	67.3	68.1	78.4	104.5	61.9	80.9	104.2	86.0	118.4	83.5	117.8	-	-	-	-
11/28/69	1525	1630	-	38.0	-	40.0	61.5	101.0	39.0	71.0	101.0	72.0	105.0	69.0	105.0	52.0	54.0	68.0	70.0
11/29/69	1435	1523	-	32.0	-	34.0	71.0	108.3	38.0	74.2	108.0	77.8	102.0	69.5	102.0	74.5	72.6	76.0	68.0
11/30/69	1053	1135	-	30.0	-	32.0	70.8	108.1	37.5	74.0	107.5	76.1	103.0	66.2	100.2	78.0	74.0	71.5	72.5
12/2/69	0945	1032	-	28.0	-	31.5	60.1	98.0	36.5	67.1	97.0	78.7	90.5	60.0	91.5	(5)	67.5	(6)	67.0
12/2/69	1430	1520	-	31.5	-	32.0	64.2	98.0	36.0	69.0	98.0	78.8	93.0	68.1	93.5	(5)	75.0	(6)	70.0
12/5/69[3]	0935	1005	-	31.0	-	31.5	-	-	-	-	-	84.2	97.2	77.9	93.0	-	-	(5)	(6)
12/6/69[3]	0830	0858	-	(4)	-	22.5	-	-	-	-	-	57.3	78.0	69.0	76.0	-	-	54.5	(5)
12/6/69[3]	1525	1555	-	38.0	-	38.2	-	-	-	-	-	64.5	83.5	75.0	84.0	-	-	59.0	(6)

(1) Value used as tower exit temperature to calculate tower range.

(2) Make-up supplied tc tower 1A only.

(3) Unit #1 shut down, not operating.

(4) Wet bulb froze.

(5) Access door frozen and could not be opened.

(6) Tower in partial use; temperature was in error due to ambient air leakage into tower.

Table A-3

Evaporation and Heat Release by Cooling Towers at Keystone

Date	Local Time	Tower Range, °F 1A	1B	2A	2B	Ambient Air Relative Humidity, % Start	Finish	Tower Evaporation loss, gpm 1A	1B	2A	2B	Total	Total Heat Released 10^6 BTU/Min	Estimated Electrical Power Generated, MW/hr Unit#1	Unit#2	% rated Capacity
9/19/69	1555	-	-	-	-	56	58	-	-	-	-	-	-	-	-	-
9/20/69	1100	(1)	23.0	32.0	32.0	75	69	(1)	1980	2760	2760	9480	112	1510(2)		84
9/20/69	1515	(1)	24.5	32.5	34.3	80	78	(1)	2040	2700	2840	9480	120	1615(2)		90
9/21/69	0900	(1)	20.5	20.8	21.8	84	79	(1)	1700	1720	1800	6920	84	1140(2)		63
9/21/69	1500	(1)	18.0	22.0	20.5	50	49	(1)	1640	2040	1870	7190	75	1062(2)		59
9/22/69	1015	(1)	24.0	24.0	24.5	80	74	(1)	2080	2080	2140	8380	98	1318(2)		73
9/22/69	1405	(1)	23.5	24.0	23.5	54	53	(1)	2190	2240	2190	8810	95	1280(2)		71
9/23/69	1030	(1)	23.3	32.1	33.8	76	73	(1)	2020	2780	2940	9760	113	1525(2)		85
9/23/69	1545	(1)	24.5	33.2	33.2	71	62	(1)	2250	3050	3050	10600	116	1560(2)		87
9/24/69	0850	(1)	24.1	32.3	33.7	99	89	(1)	2080	2800	2930	9890	115	1550(2)		86
9/24/69	1040	(1)	24.1	32.3	34.1	91	84	(1)	2130	2870	3030	10160	115	1550(2)		86
9/24/69	1340	(1)	23.3	32.4	34.3	85	83	(1)	2070	2910	3060	10110	113	1525(2)		85
11/28/69	1525	30.0	30.0	33.0	46.0	-	84	2380	2380	2650	3670	11080	145	803(3)	734(3)	85
11/29/69	1435	34.1	33.8	24.2	32.5	-	82	2580	2560	1840	2460	9440	127	804	635	80
11/30/69	1053	34.1	33.5	26.9	34.0	-	80	2500	2500	2010	2540	9550	130	796	695	83
12/2/69	0943	30.9	29.9	11.9	31.5	-	64	2840	2930	900	2380	8950	120	803	535	77
12/2/69	1430	29.0	29.0	14.2	25.4	-	95	2500	2500	1040	1870	7910	108	803	535	77
12/5/69(4)	0935	-	-	8.0	15.1	-	90	-	-	600	1040	1640	22	-	239	13
12/6/69(4)	0830	-	-	20.7	7.0	-	-	-	-	1540	300	1880	28	-	289	16
12/6/69(4)	1525	-	-	19.0	9.0	-	97	-	-	1400	800	2220	28	-	289	16

(1) Value assumed to be identical to tower 1B because of exit temperature reduction by make up water.

(2) Value calculated from BTUs of heat released and the assumption that each 1000 MW of power products 1300 MW of waste heat.

(3) These values and subsequent values obtained from station data.

(4) Unit #1 shut down, not operating.

programmed to print out all essential temperatures, the information was unreliable. The temperature data for Unit #1 were out of order during the test period and could not be decoded. The data for Unit #2 appeared to indicate trends only. Further, manual checks with thermometers showed that the pond temperature varied with location and the tower inlet water temperature was subject to stratification. The wet and dry bulb ambient air temperatures supplied by the automatic unit were also in error. A further problem with the automatic data occurred at Unit #1 where the make-up water was piped directly to the tower pond. Because the make-up water temperature was invariably cooler than the pond, the recorded temperature did not reflect true tower performance. As all make-up water was fed to tower 1A, it had to be assumed that the pond temperature of this tower was the same as for tower 1B. This was not a problem with Unit #2 nor with manually obtained data.

Natural draft towers are designed so a chimney effect is produced inside the tower shell. The density difference between the air entering and leaving the tower and the effective tower height provide the driving force from the natural draft. Water is sprayed into the tower and emerges at the base at a lower temperature; it is subsequently recycled or held in a storage basin. The thermodynamic properties of the ambient air have a significant effect on the natural draft driving force (Reference A-1).

The effect of wet bulb temperature and relative humidity is shown in Figure A-4. Climatic conditions favorable to the efficient operation of natural draft cooling towers are a low ambient temperature and a high relative humidity. This dependence on climatic conditions has limited the use of natural draft towers to locales where the ideal conditions are met during peak demands for power. In the United States peak power demands occur in the summer, and the climatic conditions are unfavorable to the efficient use of natural draft towers.

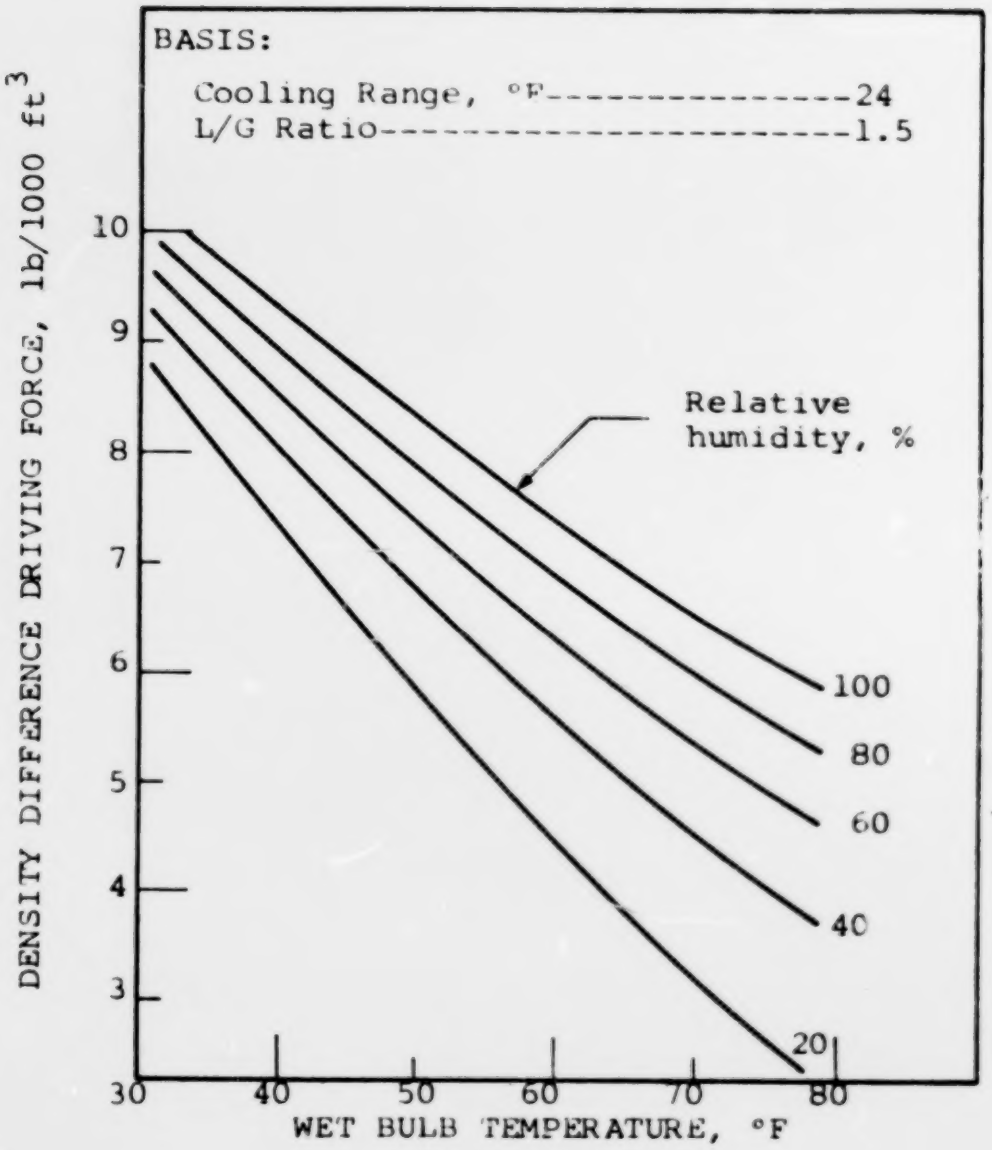


Figure A-4: The Effects of Wet Bulb Temperature and Relative Humidity on Density Difference Driving Force.

Reference

A-1. Campbell, J. S. "A New Look at Cooling Towers for the Power Generation Industry" Cooling Tower Institute Meeting, Jan. 19-22, 1968, Houston, Texas.

Appendix B

Aerial Survey: Equipment, Procedures, Results

Aerial Survey: Equipment, Procedures, Results

The purpose of the aerial survey was to sample contents of the cooling tower plumes and determine their diffusion pattern. The results were to be related to tower operation and their effect on the local climate and the emissions from the power station stacks.

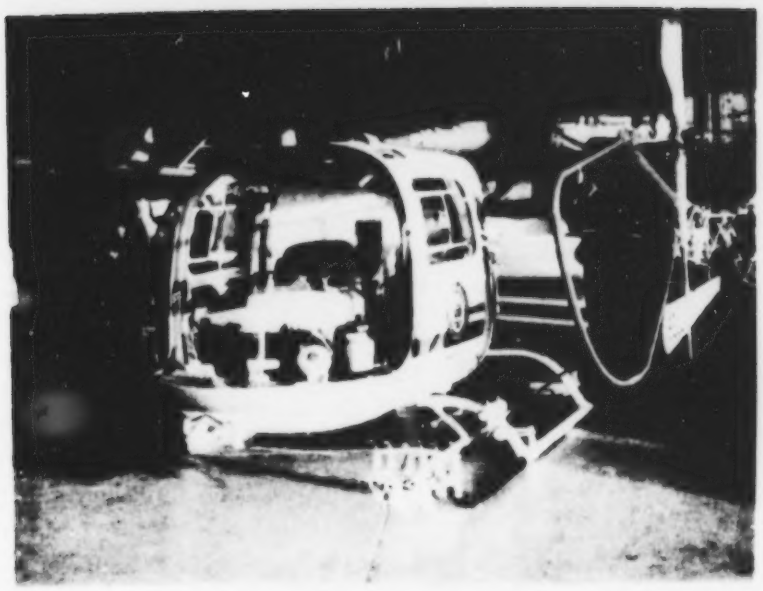
A Bell J-2 helicopter, leased from the Keystone Helicopter Corporation of Philadelphia, was instrumented for the aerial studies. The aircraft was instrumented to measure dry bulb temperature, wet bulb temperature, relative humidity, sulfur dioxide, and size and acidity of the droplets in the visible plume. The equipment used for these measurements is given in Table B-1. The instrumentation was installed by Keystone Helicopter personnel; Analytical Services Corporation, New Castle, Delaware, was retained to make sure that the installation met the Federal Aviation Administration's regulations. The electrical power for the instrumentation was supplied by a gasoline-driven generator mounted external to the aircraft. The temperature and humidity sensors and the cascade impactor used to collect plume droplets were mounted on a probe on the port side of the aircraft. The probe was designed so that it could be moved forward up to 3 meters in front of the helicopter while in-flight. At this distance and at flying speeds between 50-55 knots, the plume would be undisturbed by the rotor action (References B-1,B-2). Figure B-1 shows the probe and power generator mounted on the aircraft. Figure B-2 shows a close-up photograph of the probe and the interior installation.

The cascade impactor was used to collect droplets from the visible plume. The impactor slides were coated with a gelatin film containing a pH indicator. Droplet impressions and color changes were preserved for later evaluation. The pH indicator gave distinctive colors when the droplet pH was in the range of pH 6-7, pH 4-5, and pH 2-3. The technique used to coat the

Table B-1

Monitoring Equipment Mounted in the Bell J-2 Helicopter

Item Measured	Equipment
Wet and dry bulb temperatures	Sign X temperature and wet bulb depression sensors with a Hewlett-Packard recorder
Relative humidity	American Instrument Company hygrometer and Moseley chart recorder
Sulfur dioxide	Davis SO_2 monitor with a Bausch and Lamb recorder
Droplet collection	Casella cascade impactor with treated slides (Appendix C)



NOT REPRODUCIBLE

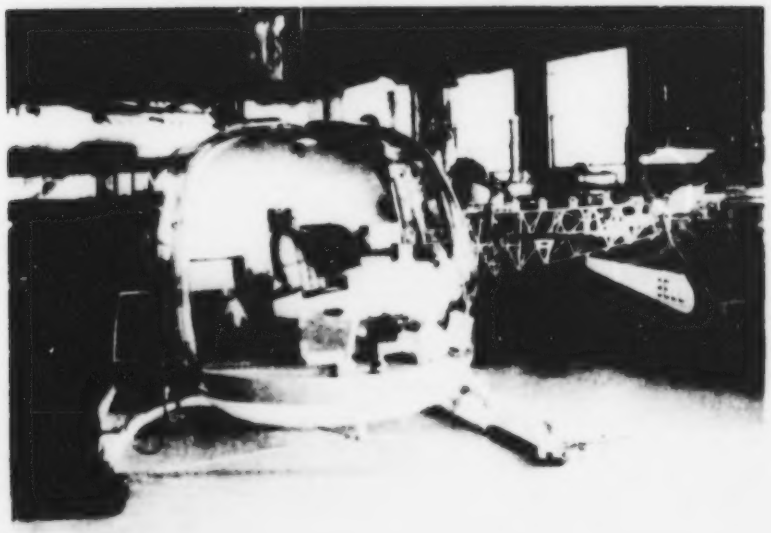
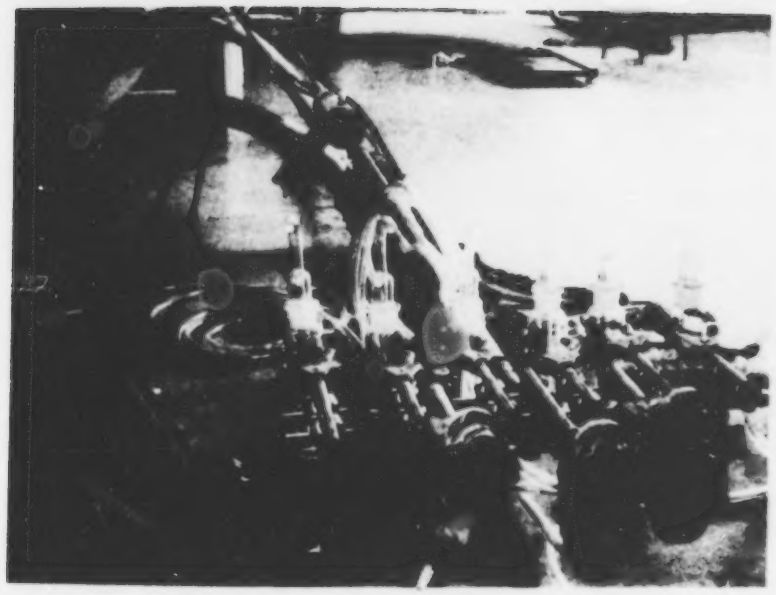


Figure B-1: The Helicopter used for Aerial Sampling.



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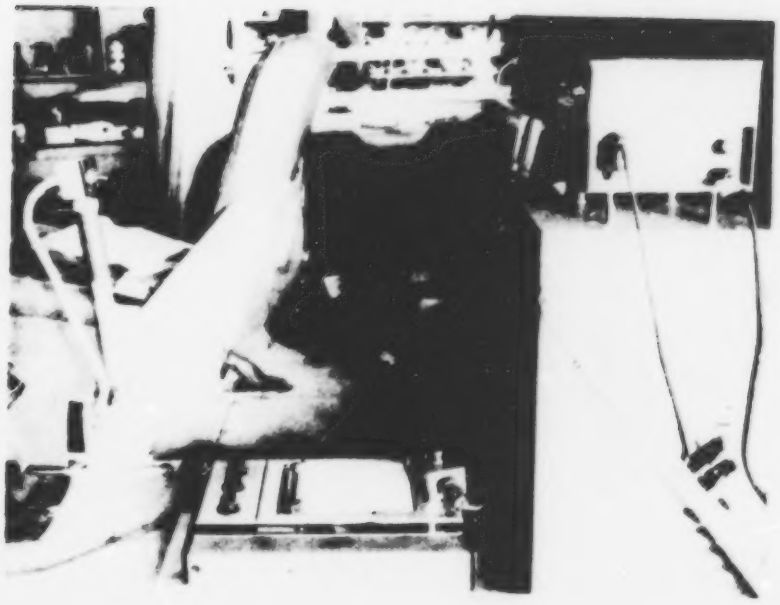


Figure B-2: Sampling Probe and Interior Installation of Equipment in the Helicopter.

slides is given in Appendix C. The Casella impactor is a four-stage impactor. The efficiency of each stage for droplets of unit density is given in Table B-2.

A plume monitoring flight pattern, Figure B-3, was adopted. The pattern was initiated by a vertical ascent upwind of the Keystone station. The ascent gave data on ambient variations in temperature, wet bulb depression, relative humidity, and sulfur dioxide. The plume was then sampled as shown in Figure B-3. A constant air speed of either 50 or 55 knots was maintained throughout the plume traverses. After the traverses of the plume were completed, the aircraft backtracked at tree-top level beneath the plume to record ground-level data. Visual navigation was used to locate the position of the aircraft during the survey. Flying within the visible plume was not possible because of excessive turbulence. Therefore, all traverses were made downwind of the visible portion of the plume. Plume droplet samples were obtained at the edges of the visible plume.

A calendar of events for the aerial survey is given in Table B-3. Weather conditions at Keystone during November and December 1969, were extremely poor and severely restricted flying time. Only three complete traverses were possible during this period. One of these traverses was made on December 2, and two were made on December 6, 1969. The December 6 AM-data were the most complete and are described in Figures 7 through 17 in the body of the report. The data from the other plume traverses are presented in Figures B-4 to B-21. No ground-level traverse beneath the plume was made on December 2, 1969, due to deteriorating weather conditions. All plume profiles are drawn as if viewed from the cooling towers and looking downwind along the plume axis. The Keystone station was operating at 77% of rated capacity on December 2, and at 16% on December 6, 1969. Surface and upper wind data for the survey data are given in Tables B-4 and B-5. Droplet data are presented in Appendix C.

Table B-2

Efficiency of the Cascade Impactor Stages

Stage	Cut-off droplet size, μm (1)
1	12
2	4
3	2
4	1.1

(1) 50% of the droplets this size will evade collection at the design flow rate.

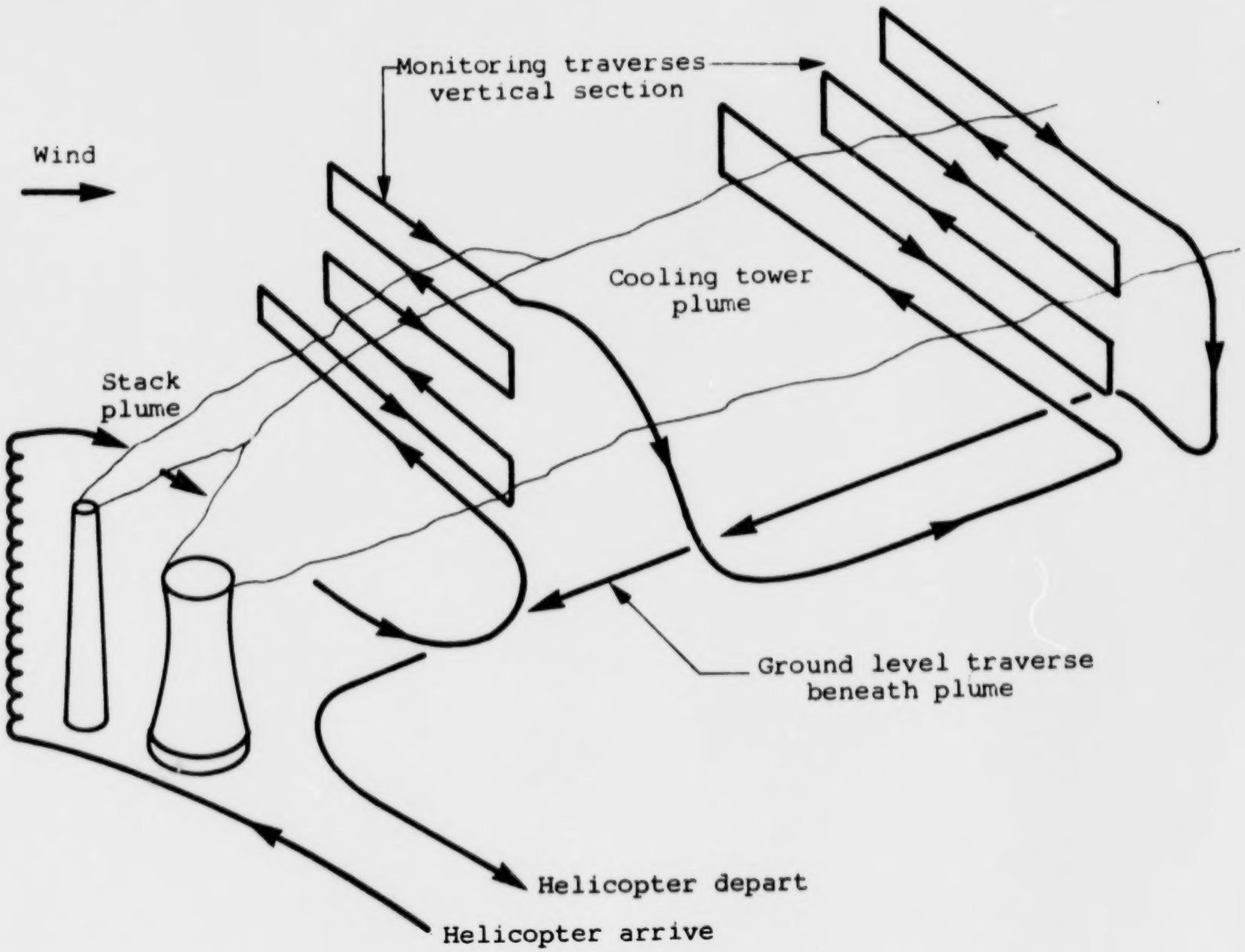


FIGURE B-3: Plume Monitoring Pattern.

Table B-3

Aerial Survey: Calendar of Events

Date	Comments	Flying Time
11/24/69 Mon.	Helicopter ferry time, Philadelphia partway to Keystone	1.1
11/25/69 Tues.	Ferry time. Helicopter arrived at Keystone	2.7
11/26/69 Wed.	Checkout instruments & APU Familiarization with local area	1.7
11/27/69 Thurs.	Thanksgiving	No flying
11/28/69 Fri.	Initiated plume traverses. Unable to attain sufficient altitude due to poor visibility	2.1
11/29/69 Sat.	Weather unsuitable	No flying
11/30/69 Sun.	Partial plume traverses & samples	1.6
12/1/69 Mon.	Weather unsuitable	No flying
12/2/69 Tues.	Plume traverses & samples. Low stratus	3.4
12/3/69 Wed.	Weather unsuitable	No flying
12/4/69 Thurs.	Weather unsuitable	No flying
12/5/69 Fri.	Weather unsuitable: plume samples only	1.7
12/6/69 Sat.	Plume traverses & samples	4.7
12/7/69 Sun.	Remove equipment from helicopter. Return to Chicago	
	Total flying time	19.0 hours

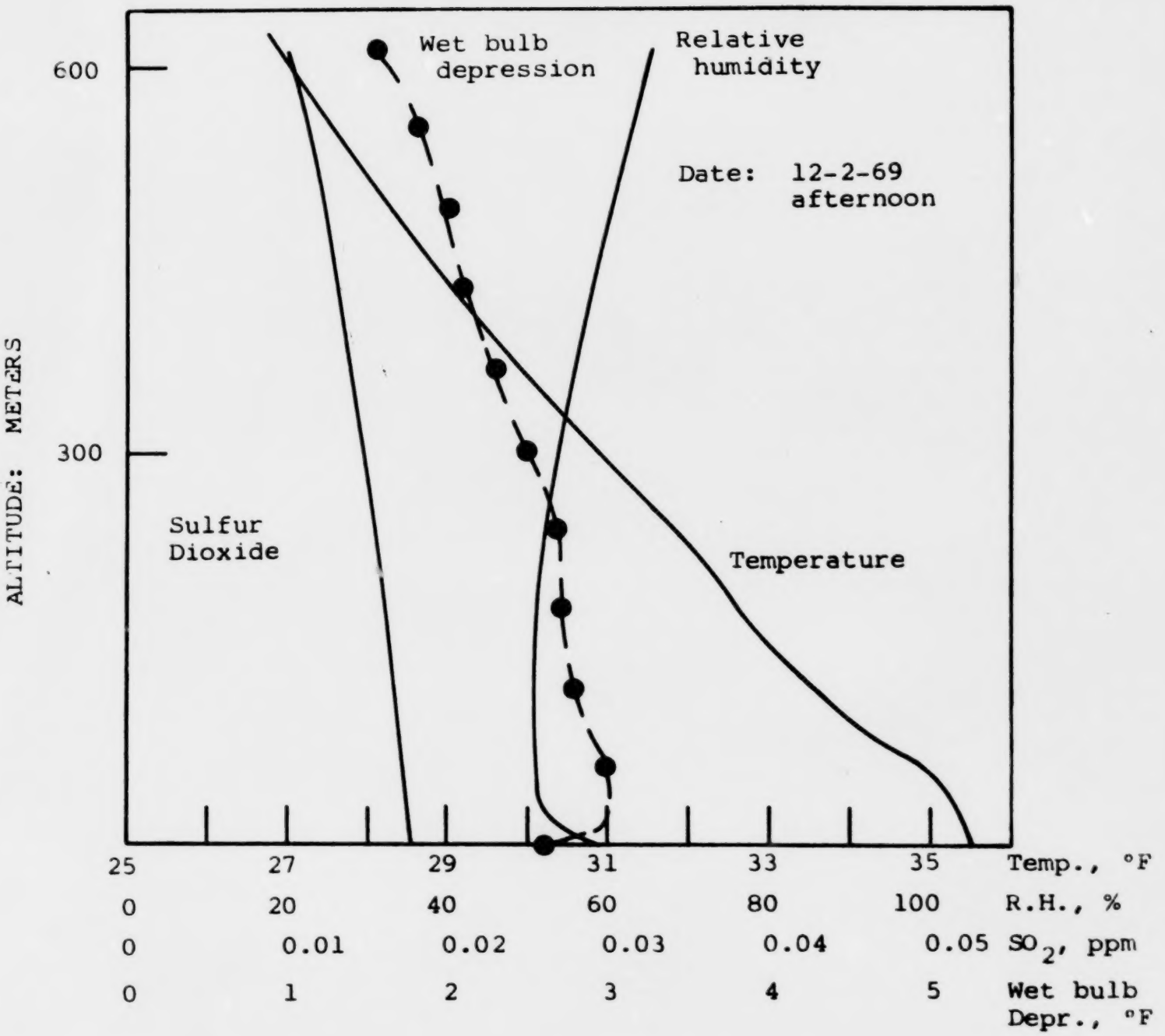


Figure B-4: Prevailing Ambient Conditions Prior to Plume Traverses.

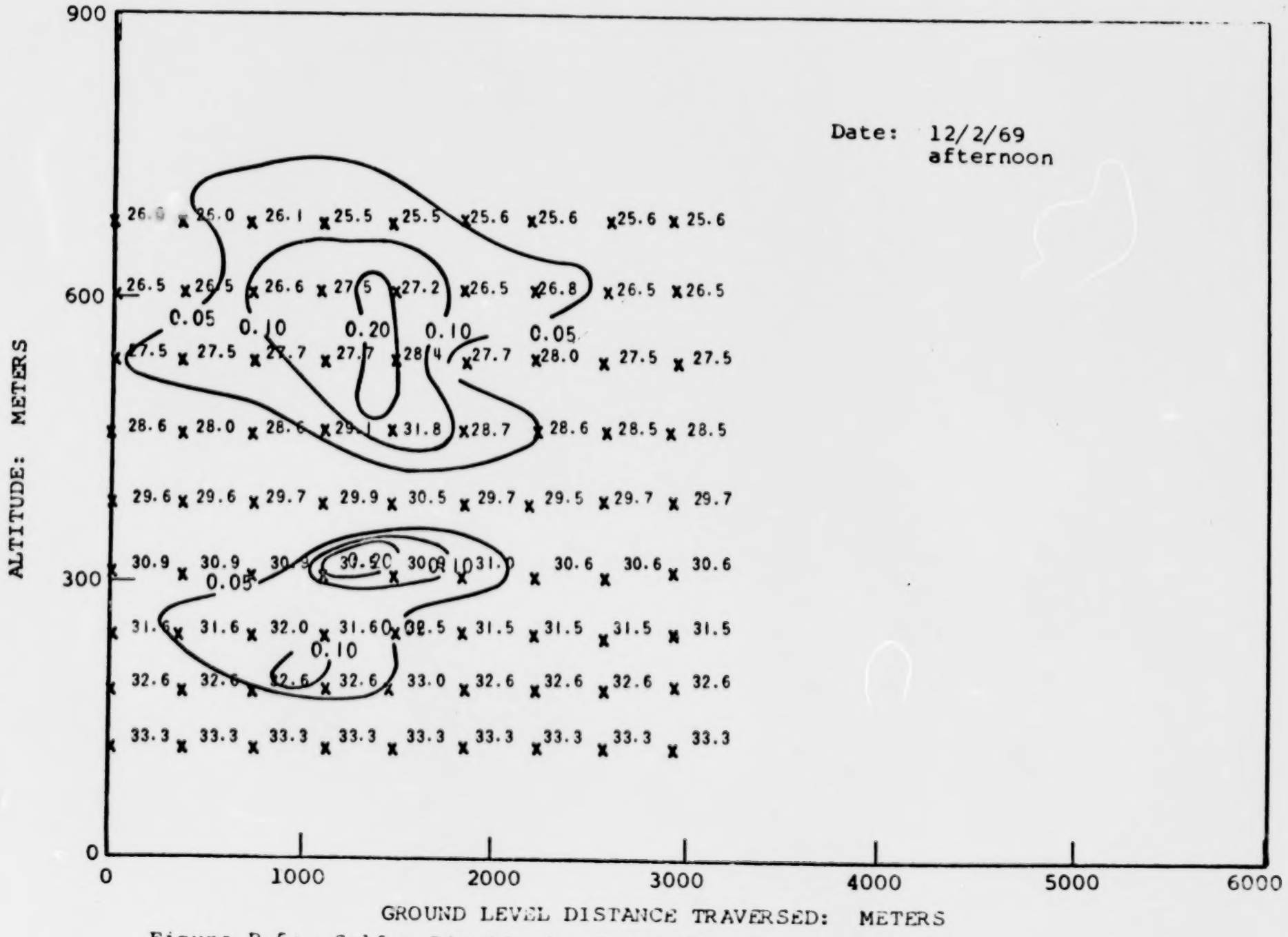


Figure B-5: Sulfur Dioxide (ppm) Profile
at 2093 Meters Downwind of Tower.

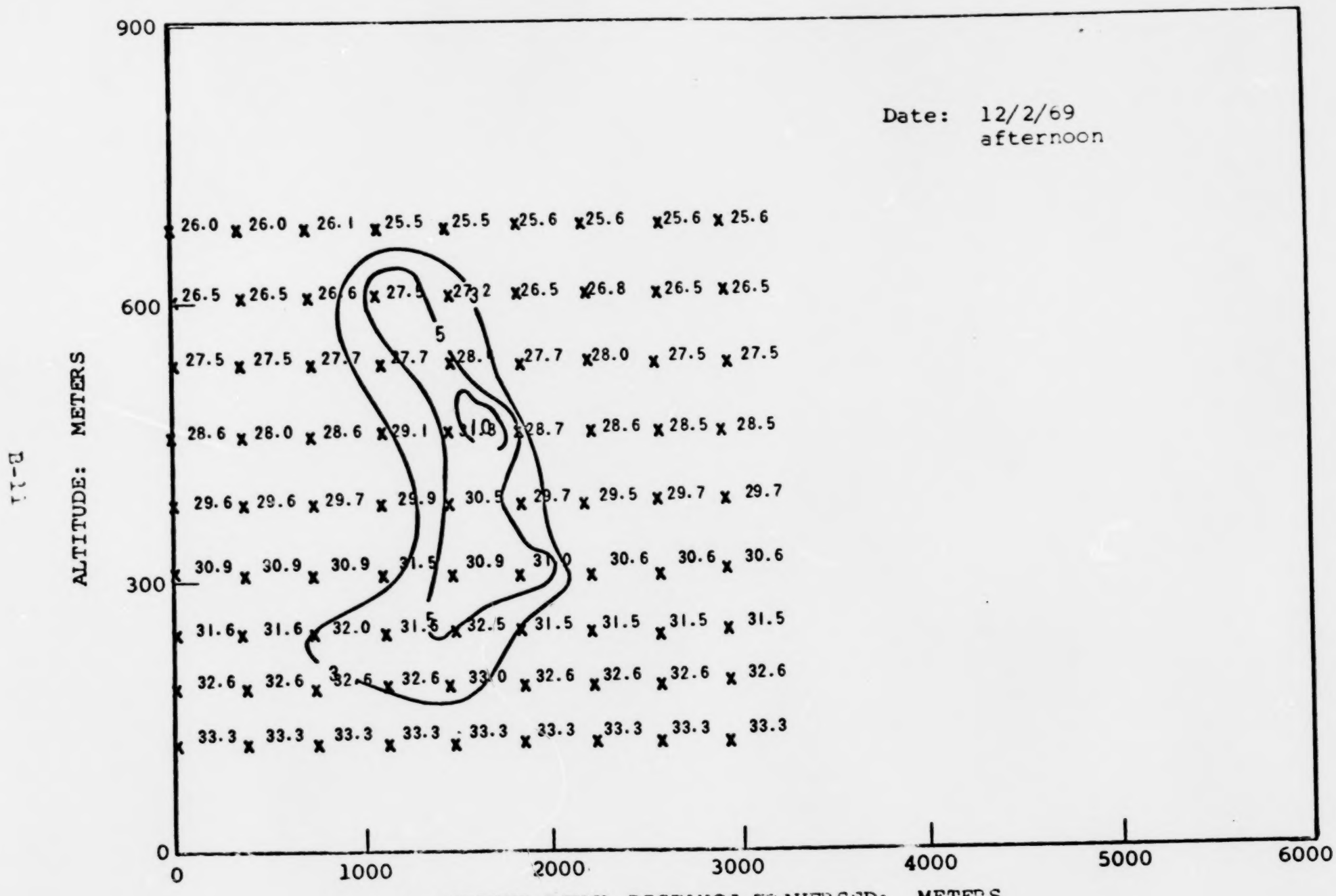


Figure B-5: Relative Humidity Profile (% point above background) at 2093 Meters Downwind of Tower

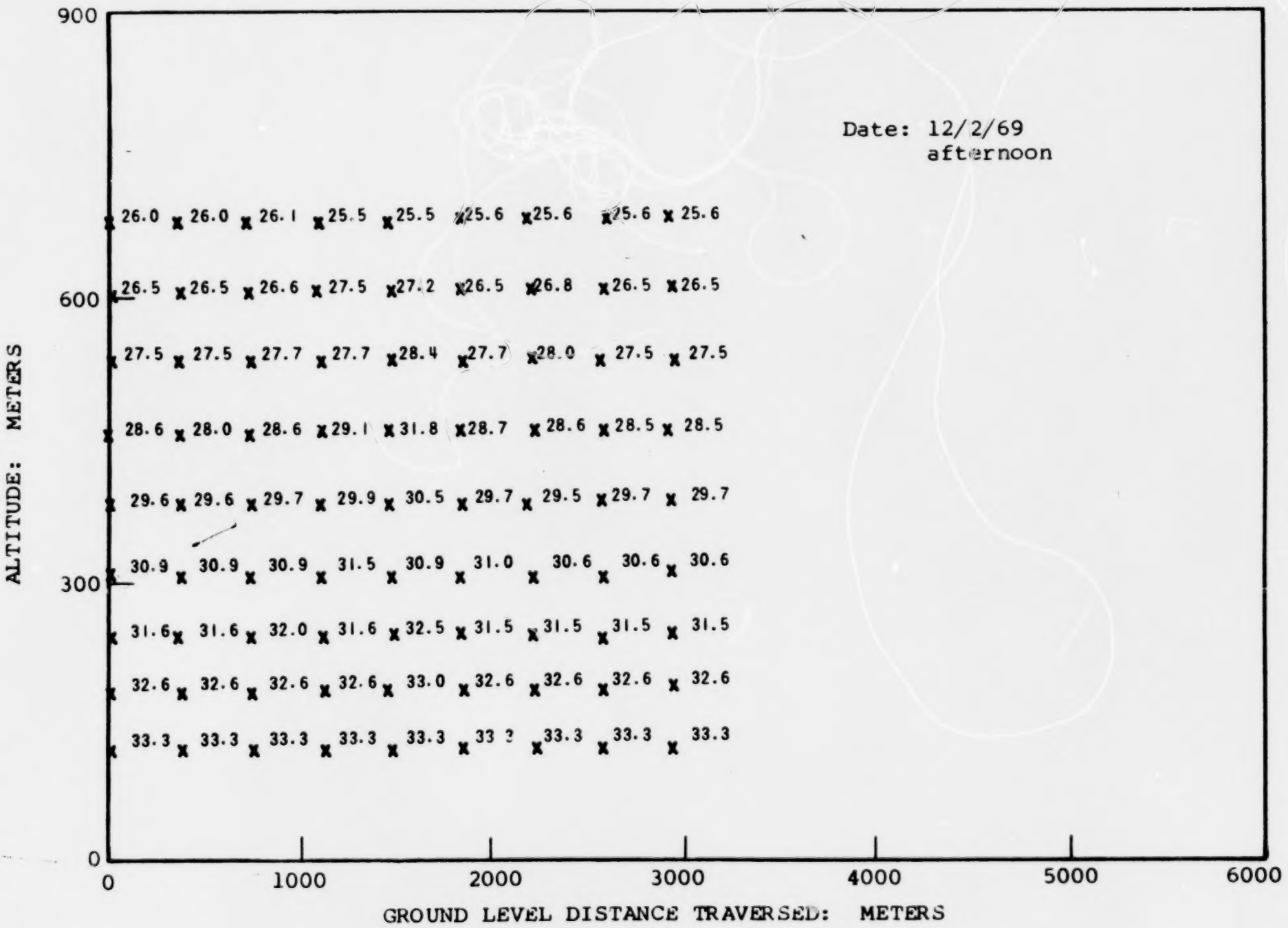


Figure B-7: Temperature Profile (°F) at 2093 Meters Downwind of Tower.

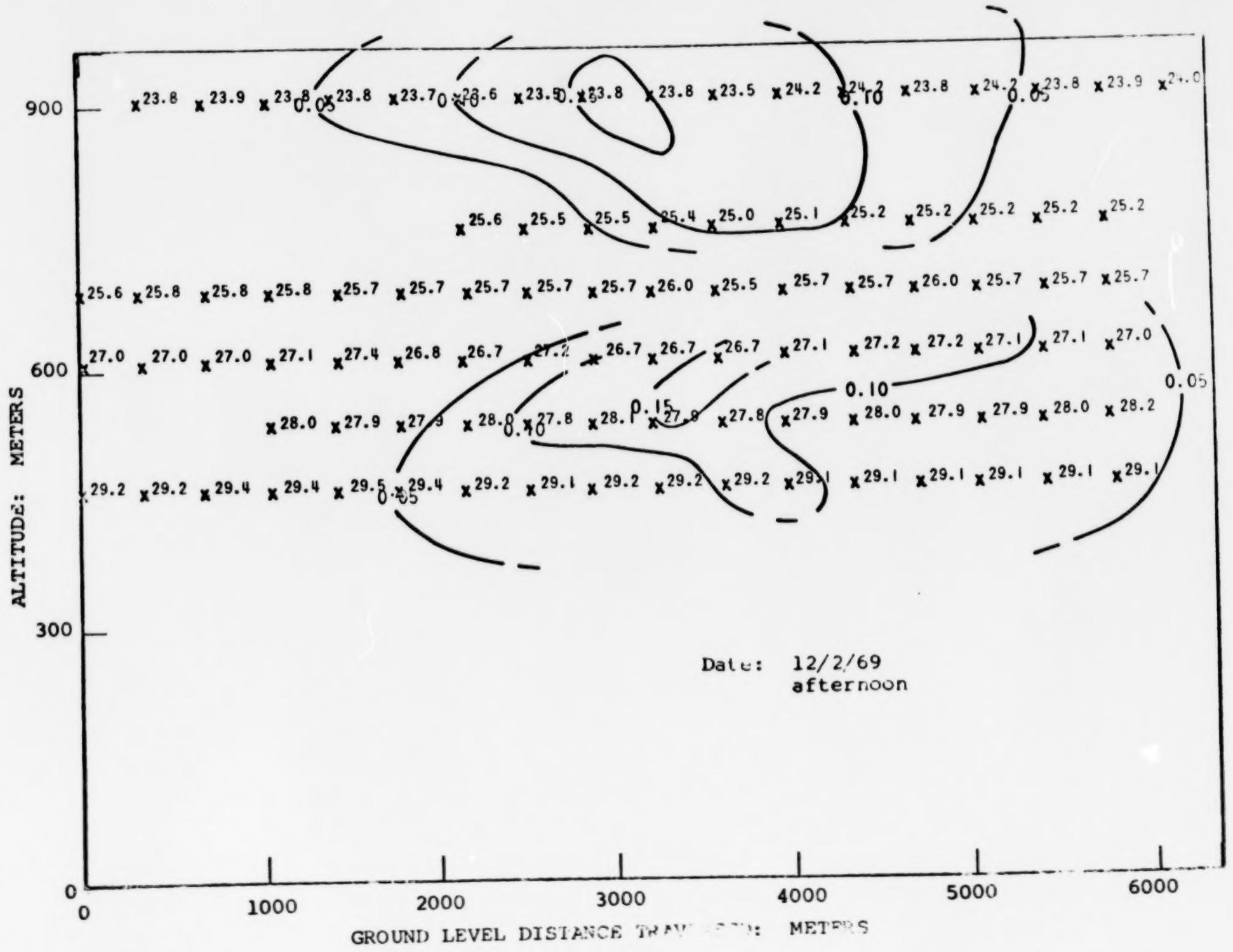


Figure B-8: Sulfur Dioxide (ppm) Profile at 9960 Meters Downwind of Tower.

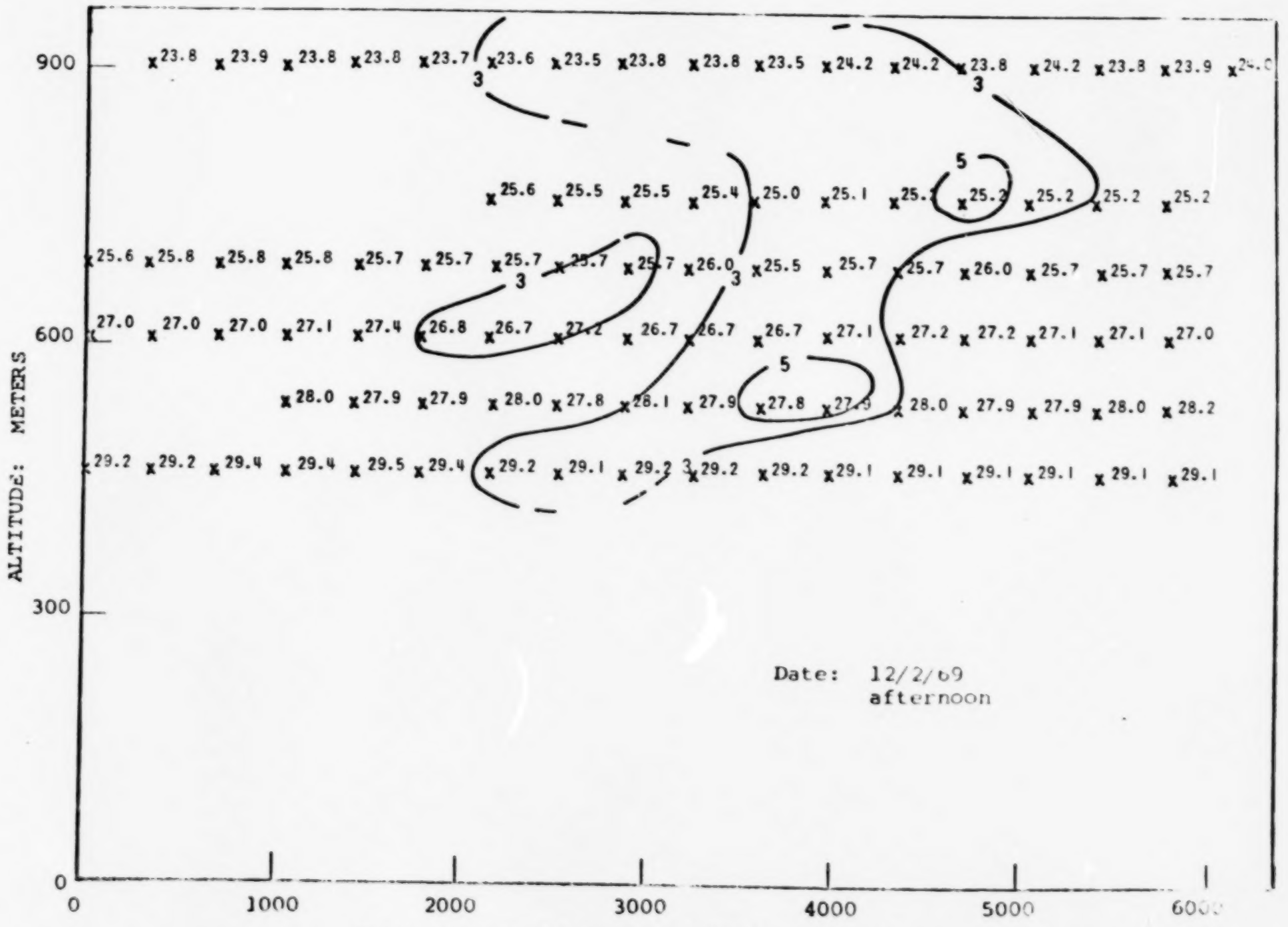


Figure B-9: Relative Humidity Profile (% point above backgr
at 9[illegible] Meters Downwind of Tower.

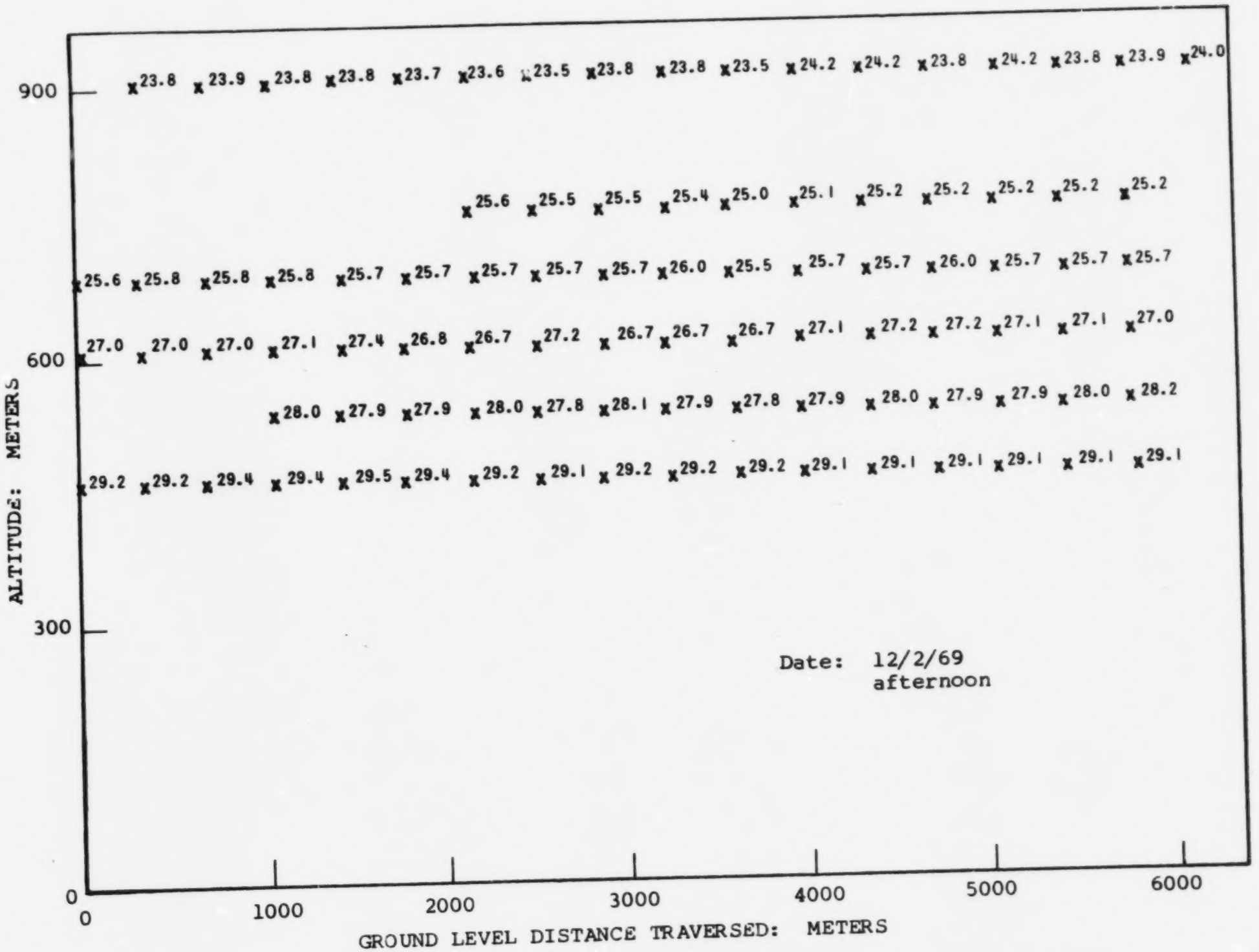


Figure B-10: Temperature Profile (°F) at 9960 Meters Downwind of Tower.

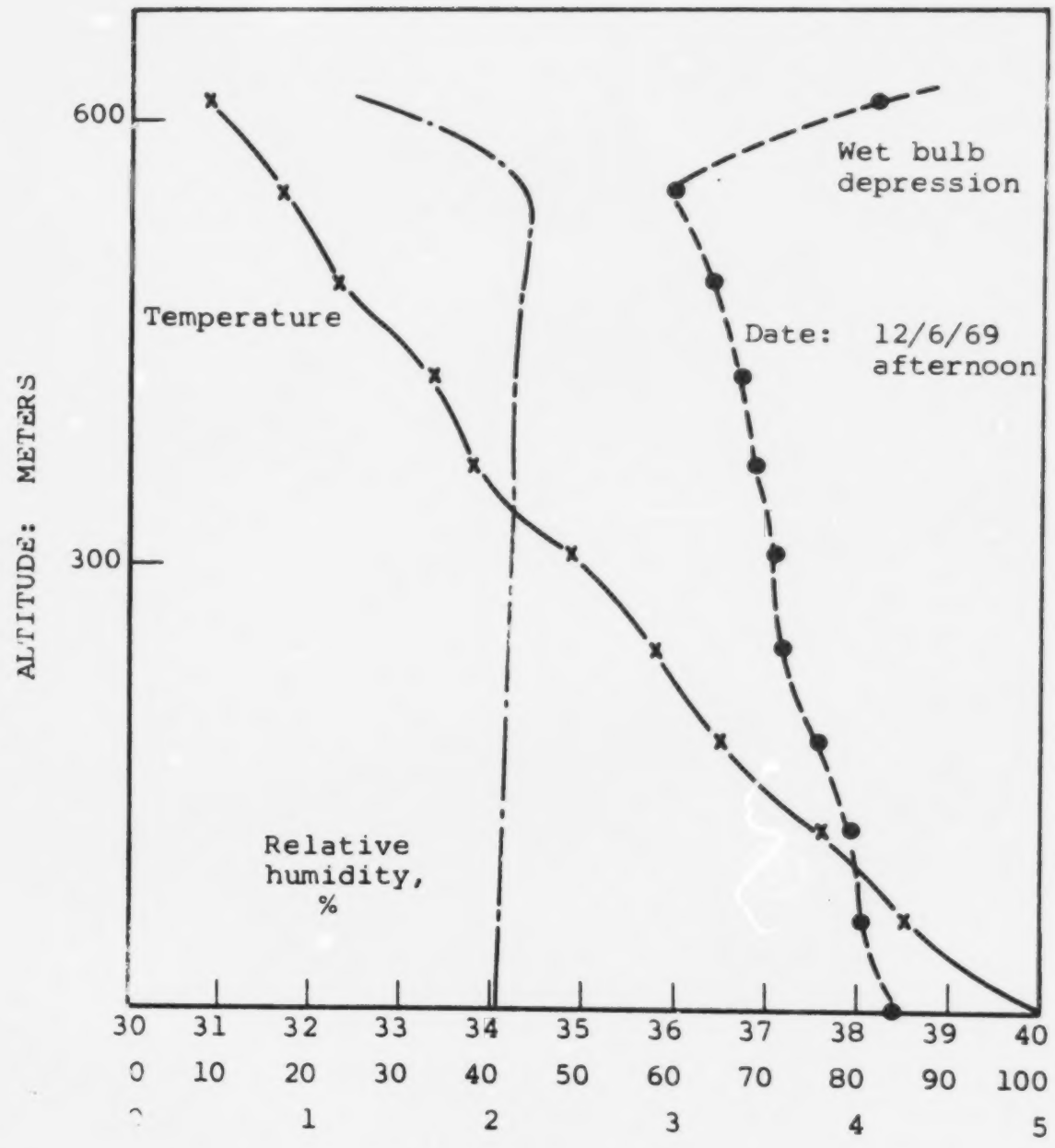


Figure B-11: Prevailing Ambient Conditions Prior to Plume Traverses.

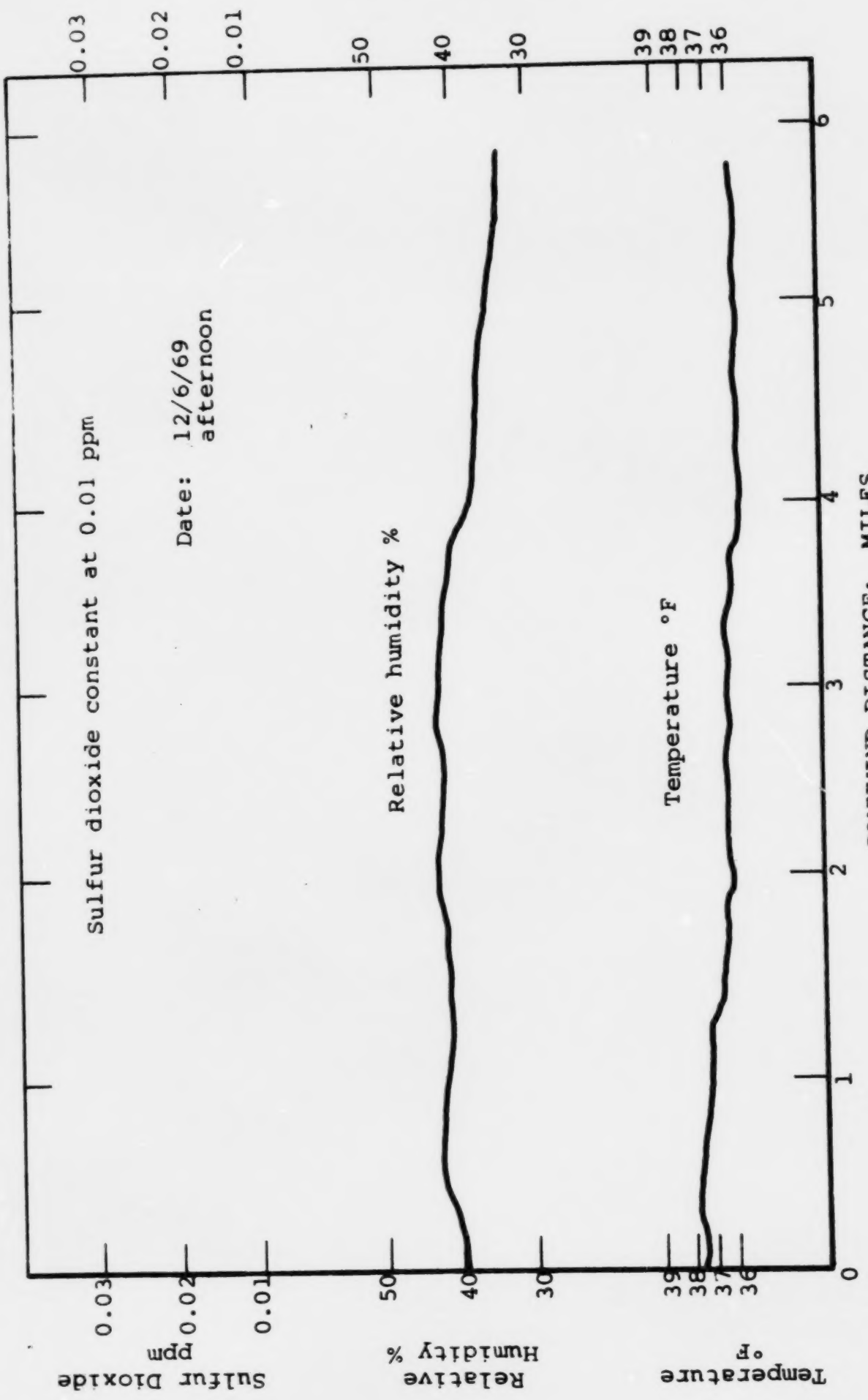


Figure B-12: Ground Level Traverses Beneath Plume.

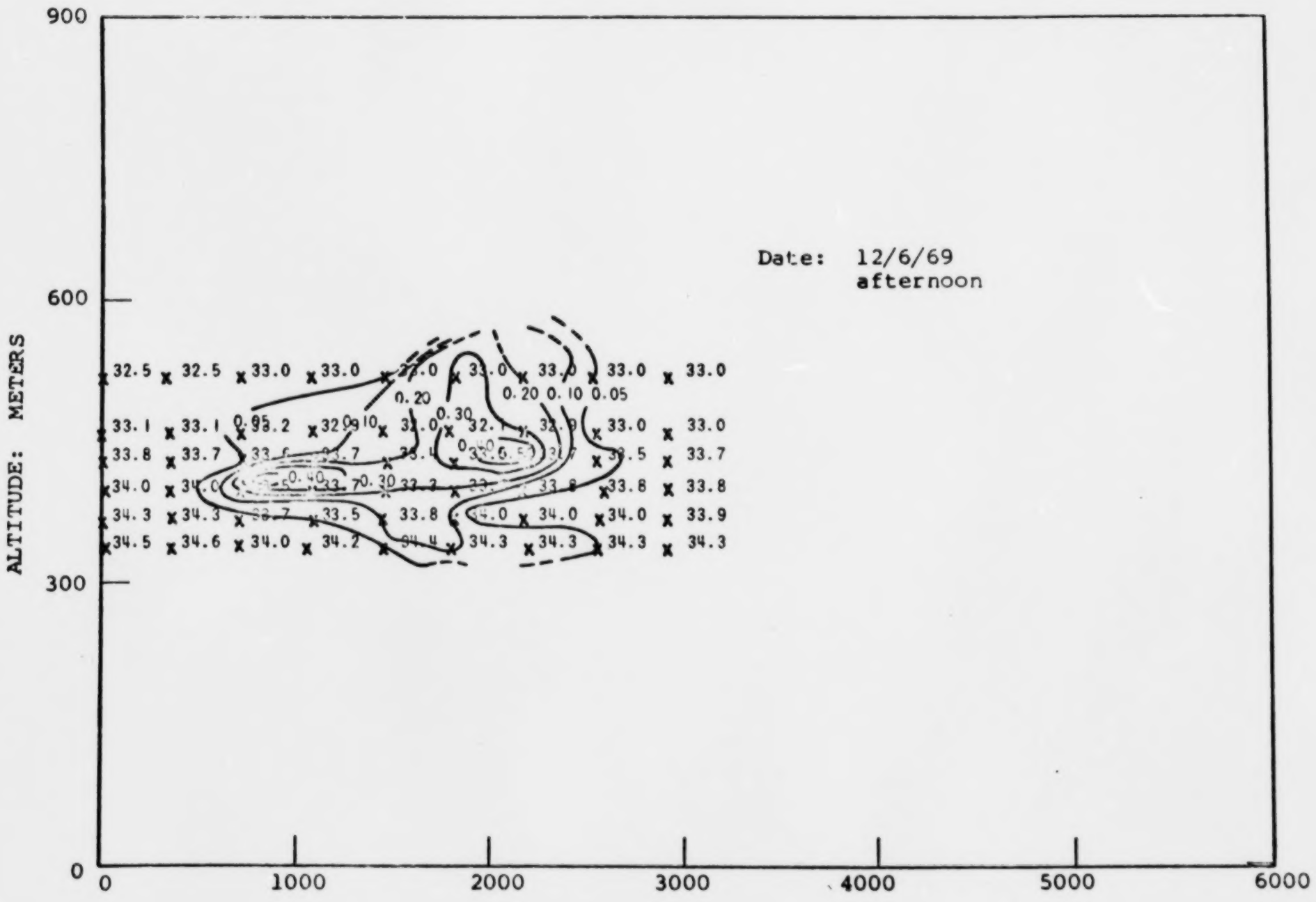


Figure B-13: Sulfur Dioxide (ppm) Profile
at 644 Meters Downwind of Tower.

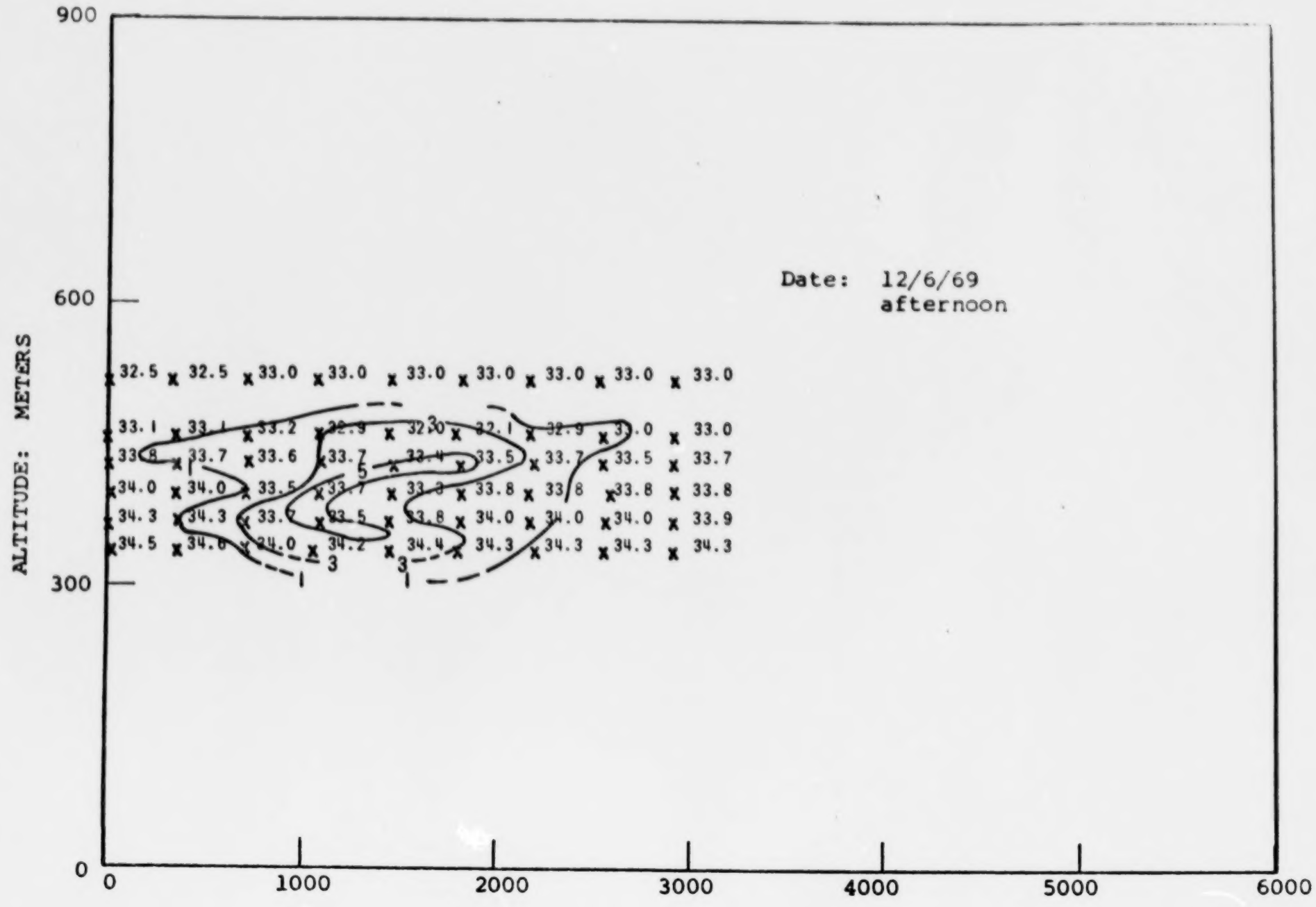


Figure B-14: Relative Humidity Profile (% point above background) at 644 Meters Downwind of Tower.

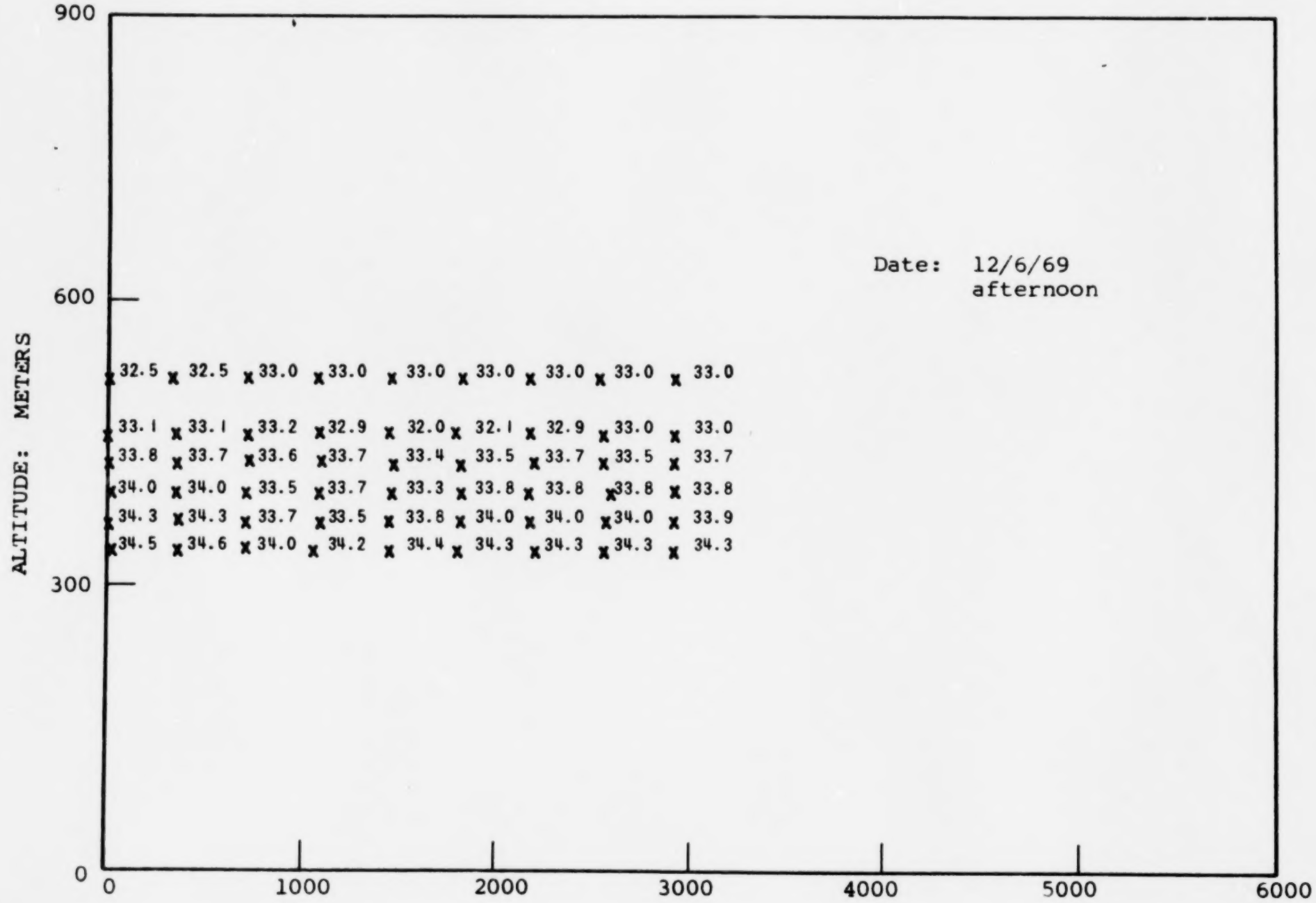


Figure B-15: Temperature Profile (°F) at 644 Meters Downwind of Tower.

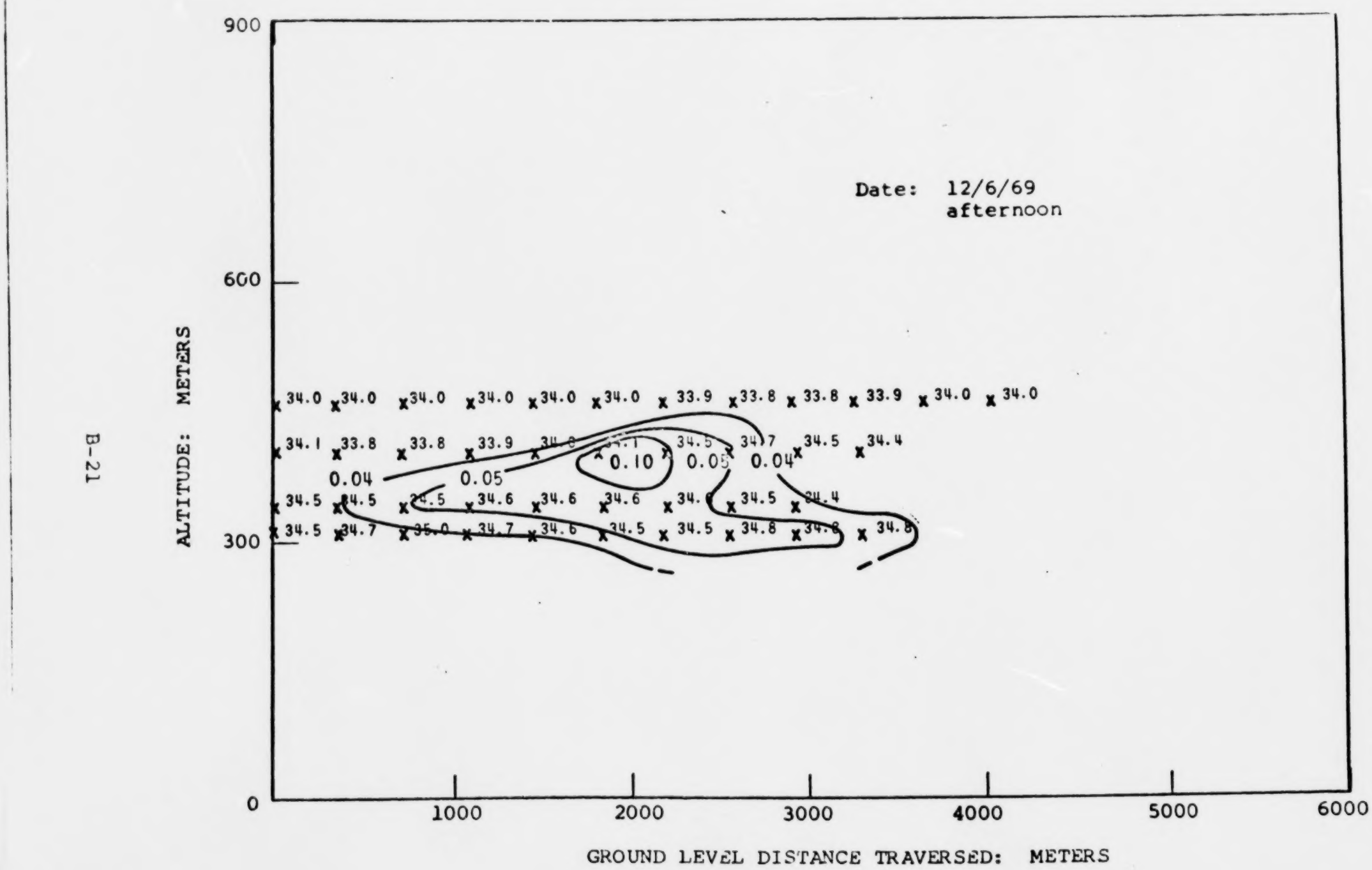


Figure B-16: Sulfur Dioxide (ppm) Profile at 3220 Meters Downwind of Tower.

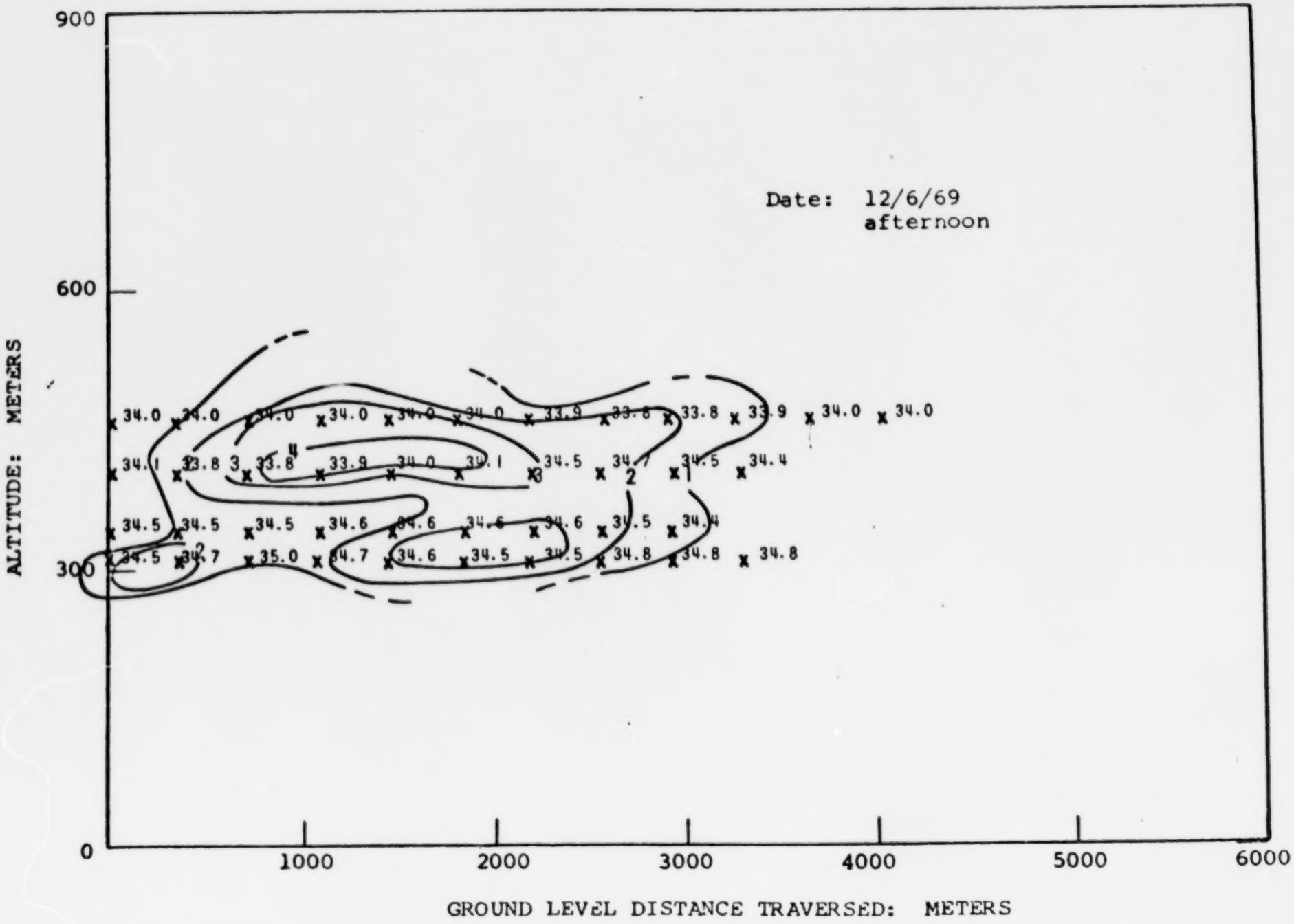


Figure B-17: Relative Humidity Profile (% point above background) at 3220 Meters Downwind of Tower.

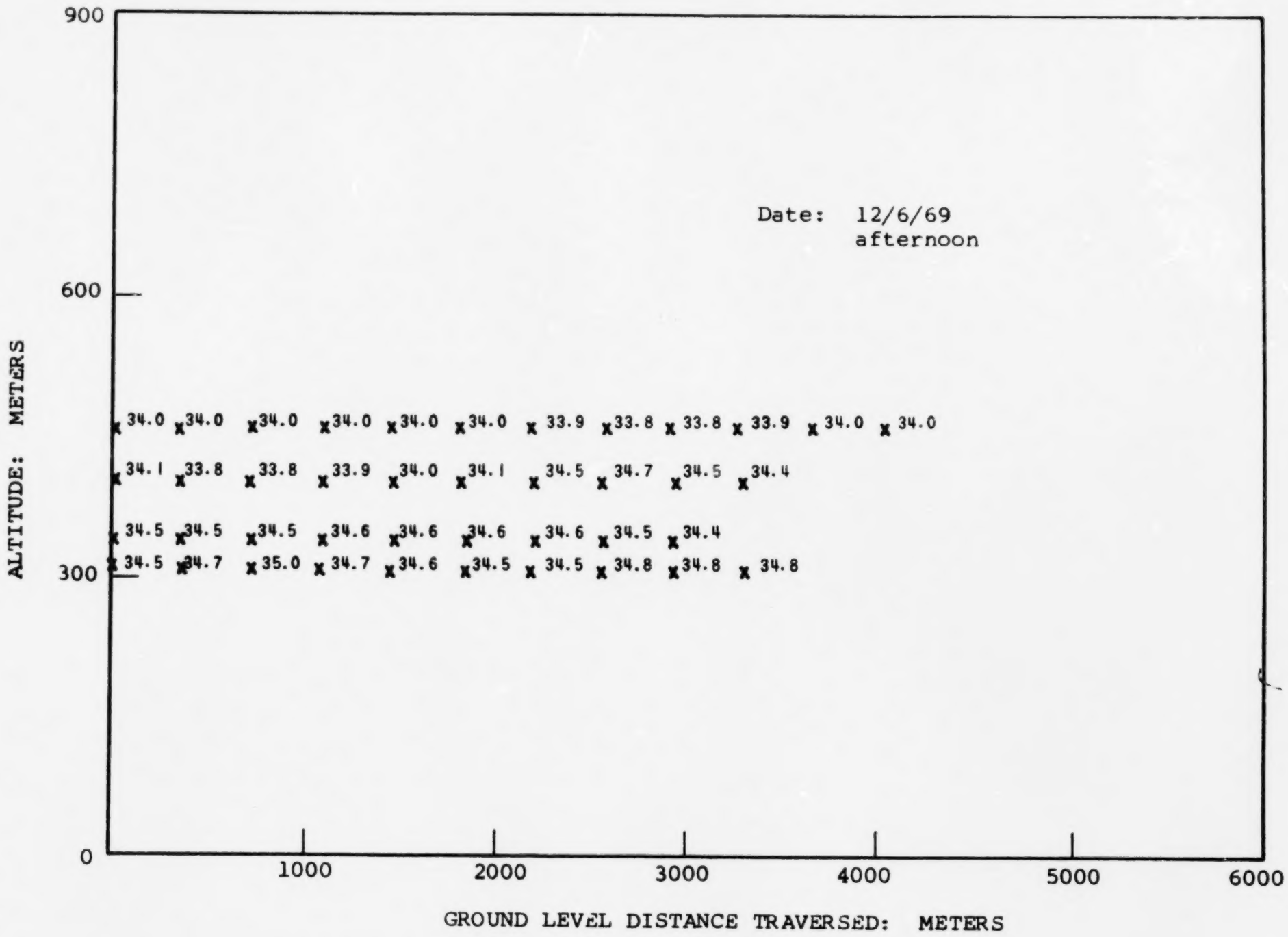


Figure B-18: Temperature Profile (°F) at 3220 Meters Downwind of Tower.

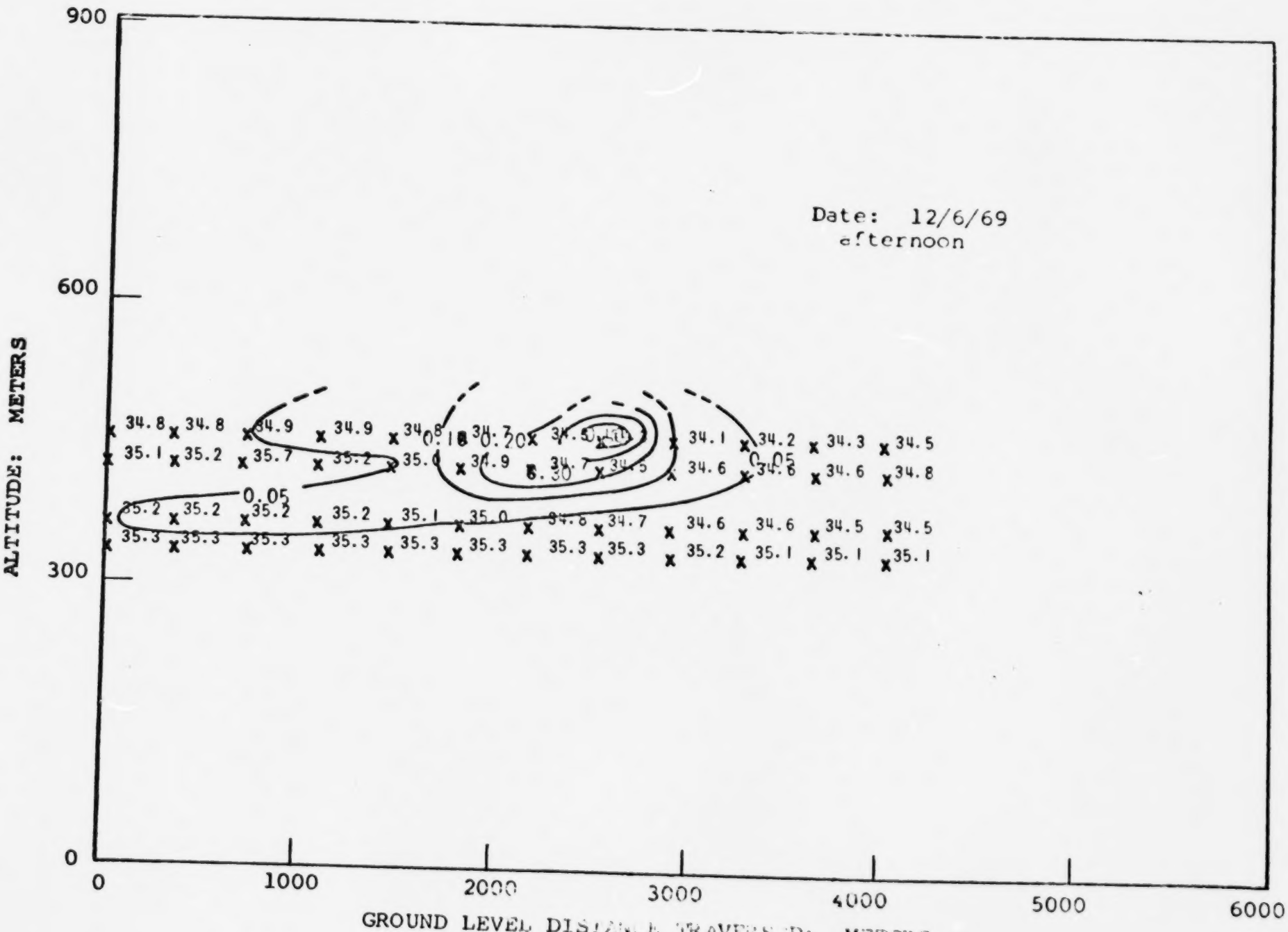


Figure B-19: Sulfur Dioxide (P[illegible]) at 10,765 Feet Downwind from Tower.

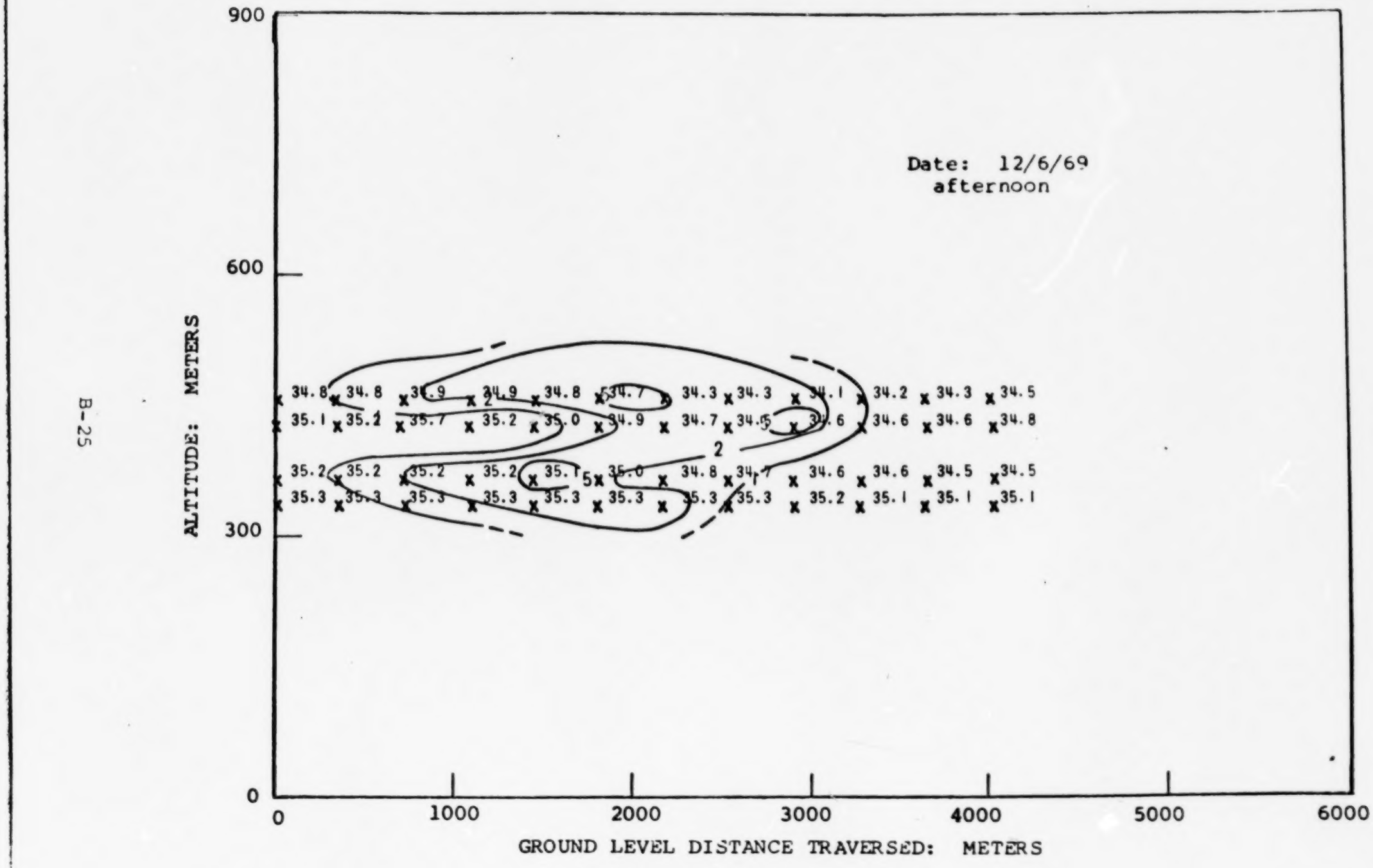


Figure B-20: Relative Humidity Profile (% point above background) at 10,765 Meters Downwind of Tower.

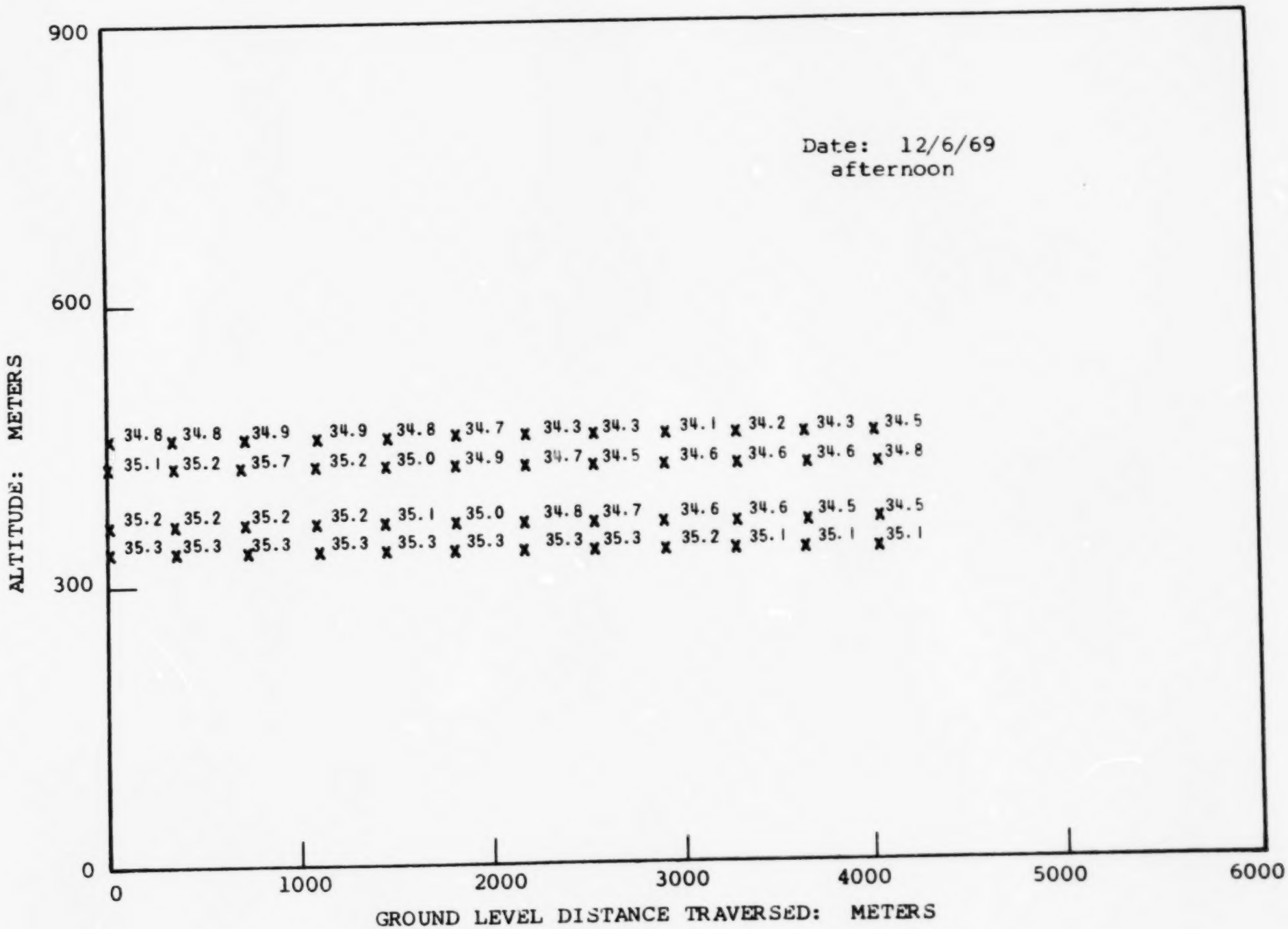


Figure B-21: Temperature Profile (°F) at 10,765 Meters Downwind of Tower.

Table B-4

Surface Winds at Pittsburgh, Altoona, and Blairsville, Pa.

12/2/69

Pittsburgh (Airport)			Altoona, Pa.			Blairsville, Pa.		
	Wind			Wind			Wind	
Local Time	Direction 00-36	Speed Kts	Local Time	Direction 00-36	Speed Kts	Local Time	Direction 00-36	Speed Kts
1207	23	16	1158	30	13	1150	24	09
1255	22	17	1258	30	12	1248	22	09
1310	22	13	1358	28	12	1350	20	13
1355	22	19	1459	27	10	1448	20	20
1419	23	16	1557	25	13	1550	23	16
1455	21	18	1658	28	10	1650	23	12
1555	24	14						
1619	25	14						
1656	24	16						
			12/6/9					
0755	00	00	0757	25	04	0751	06	05
0858	04	04	0858	29	05	0850	07	05
0958	05	07	0956	00	00	0948	08	07
1058	05	10	1058	00	00	1050	10	05
1158	06	09	1158	00	00	1151	08	06
1258	05	07	1258	00	00	1250	10	07
1358	06	08	1357	00	00	1352	09	08
1458	06	07	1458	00	00	1452	10	08
1558	06	07	1558	00	00	1550	11	11
1658	06	07	1656	06	06	1648	10	12

Table B-5

Upper Air Winds at

Pittsburgh, Pa.

Date	Local Time	Height, Meters	Wind Direction 00-360°	Wind Speed Kts
12/2/69	1115	608	30	12
		912	30	13
		1215	30	13
	2315	608	240	26
		912	255	37
		1215	265	43
12/5/69	2315	608	330	11
		912	330	11
		1215	340	10
12/6/69	1115	608	09	12
		912	09	12
		1215	09	13
	2315	608	08	14
		912	08	14
		1215	09	14

REFERENCES

B-1. Landgrebe, A.J. "An Analytical Method for Predicting Rotor Wake Geometry" J. Amer. Helicopter Soc. 14, p. 20, 1969.

B-2. Gorosko, B.B., Elisen, V.S., and Nazarewko, V.J., "On the Technique of Observations of Atmospheric Pollution by Helicopter," Leningrad, Glav. Gecf., Obs. T. Vyp. 207, p. 76, 1968.

Appendix C

Impactor Samples: Slide Preparation, Droplet Sizes and Acidity

Impactor Samples: Slide Preparation, Droplet Sizes and Acidity

Cascade impactors were used to collect plume droplets for size and acidity analysis. Samples were collected from the helicopter at the edges of the visible plume. Because of high turbulence, it was not prudent to fly within the visible portion of the plume. It was anticipated that the mixing of the cooling tower plume with the station effluent would produce acid droplets and the ratio of acid droplets to neutral droplets would provide information on the degree of mixing.

To determine droplet acidity the impactor slides were coated with a gelatin film containing a pH indicator. The method used was similar to that described by Waller (Reference C-1) and Liddell and Wootten (Reference C-2). Approximately 2 g of gelatin were wetted with a little acetone and then dissolved in 50 ml of distilled water heated in a water bottle. A solution containing 1 g of methyl red in 50 ml of 1N ammonia was mixed into the warm gelatin solution. A drop of the gelatin solution was placed on clean, glass microscope slides inclined at 45° and allowed to spread and dry as a thin film. This operation was repeated until the desired thickness of the film was achieved. Methyl red indicator was used because it gave distinct color changes at three levels of acidity as follows:

pH 6-7	clear
pH 4-5	yellow
pH 2-3	red

The color changes were tested in the laboratory using a hydraulic spray nozzle to generate neutral and mildly acid water droplets. Droplet residues on the slide were clearly apparent and did not deteriorate with time; also, no obvious fading of the color was observed for periods up to a few weeks. Subsequent tests showed that the slides did not react to the gaseous sulfur dioxide concentrations in the power station plume.

The results of the plume droplet sampling are given in Table C-1. A size distribution of the plume droplets was not possible. Most of the droplets were captured on the first impactor stage; the cut-off size for this stage is 12μm (unit droplet density). The problem is further complicated by the fly ash particles often associated with the plume droplets that would alter the density of the droplet. The sizes reported in Table C-1 are for the diameters of the residue impressions left on the gelatin film after the droplet evaporated. Their relationship to the original droplet diameter was not determined. While such a relationship is determinable, it would not apply to droplets containing rather large particulates such as fly ash. Size distributions of the residual impressions for some of the droplet collections are given in Figures C-1 through C-5. Photomicrographs of representative collections are shown in Figures C-6 and C-7.

Table C-1

Acidity and Residue Sizes of Cooling Tower Plume Droplets

Sample Number	Date	Local Time	Position of Aircraft During Sampling: Altitude,m	Position	Ambient Air Conditions: Temp.,°F	Rel.Humid.,%	SO_2, ppm	Plume air Conditions: Temp.,°F	Rel.Humid.,%	SO_2, ppm	Plumes Mixed[1]	Droplet pH and Residue Size: pH 6-7: Residue dia.,μm[4] Median	pH 6-7: Residue dia.,μm[4] Range	pH 4-5: Residue dia.,μm[4] Median	pH 4-5: Residue dia.,μm[4] Range	pH 2-3: Residue dia.,μm[4] Median	pH 2-3: Residue dia.,μm[4] Range	Ratio pH4-5 droplet / pH6-7 droplet
1	11/29/69	1100	336	end of visible plume	29.2	81	0.035	31.2	88	0.975	yes	40	10-150	35	6-275	13	4-30	1.57
2	11/30/69	1100	305	end of visible plume	29.0	83	0.035	31.7	94	0.140	yes	46	10-110	36	5-120	-	5-25[2]	1.10
3	11/30/69	1100	274	½ mile downwind of tower	30.4	84	0.035	32.1	90	0.040	no	39	10-90	29	6-90	13	3-40	1.09
4	12/2/69	1000	228	¼ mile downwind of tower	24.2	96	0.010	30.2	96	0.110	yes		10-110[2]	-	10-60[2]	(3)	-	3.00
5	12/2/69	1435	228	near unit #1 stack	30.9	58	0.018	34.0	76	0.018	no		20-500[2]	(3)	-	(3)	-	-
6	12/5/69	1425	183	200m downwind of tower	31.9	78	0.040	35.6	85	0.200	no	33	5-120	(3)	-	(3)	-	-
7	12/5/69	1425	352	400m downwind of tower	30.7	81	0.030	30.7	83	0.110	yes	165	25-350	(3)	-	(3)	-	-
8	12/5/69	1425	413	400m downwind of tower	29.5	80	0.020	31.0	85	0.295	yes	178	50-325	(3)	-	(3)	-	-
9	12/6/69	1045	183		26.2	85	0.035	30.4	92	0.035	no	(3)	-	38	10-80	(3)	-	1.3
0	12/6/69	1045	244		25.8	85	0.035	29.3	89	0.035	no	225[2]	-	(3)		(3)	-	-
11	12/6/69	1045	336	300 to 400m	25.0	85	0.035	27.2	88	0.340	yes	325	-	10	4-90	(3)	-	1.42
12	12/6/69	1230	305	downwind of tower	33.5	44	0.045	36.0	49	0.065	no	237	-	(3)		(3)	-	-
13	12/6/69	1230	216		35.6	44	0.040	41.8	62	0.040	no	220	-	(3)		(3)	-	-
14	12/6/69	1230	183		36.2	45	0.035	44.9	89	0.035	no	270	-	50	25-250	(3)	-	0.182
15	12/6/69	1240	305		34.0	43	0.35	37.6	46	1.07	yes	90[2]	-	(3)		35	10-110	-

(1) refers to the mixing of the cooling tower plume and the station effluent. Relative SO_2 concentrations were used to determine if plumes were mixed.

(2) insufficient number of droplets available for accurate size measurements.

(3) no droplets present

(4) the sizes reported are the diameters of the residue impressions left on the gelatin film after evaporation of the droplet. The relationship between the residue size and the size of droplet leaving the residue was not determined.

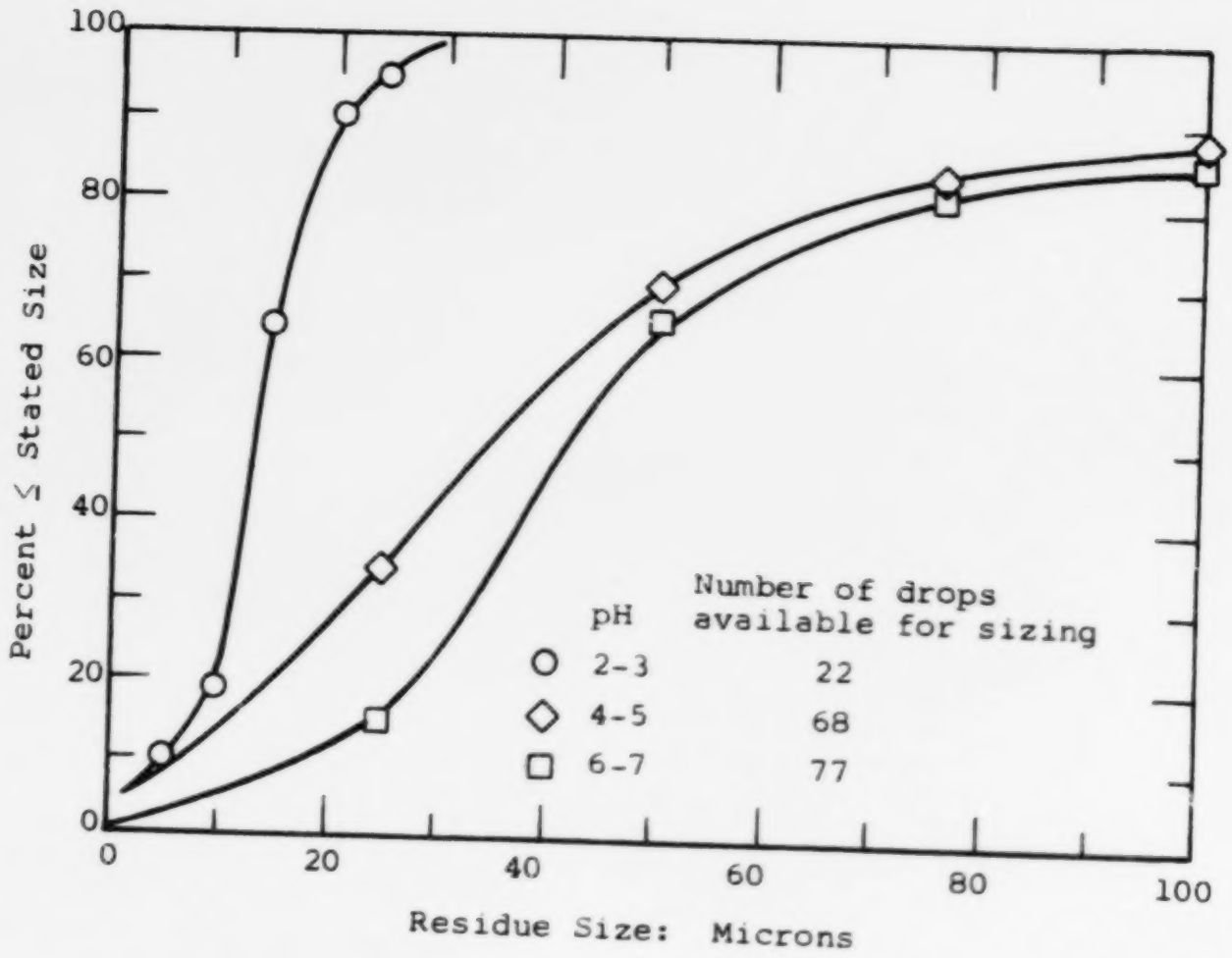


Figure C-1: Plume Droplet Residue Size Distribution Sample Number 1.

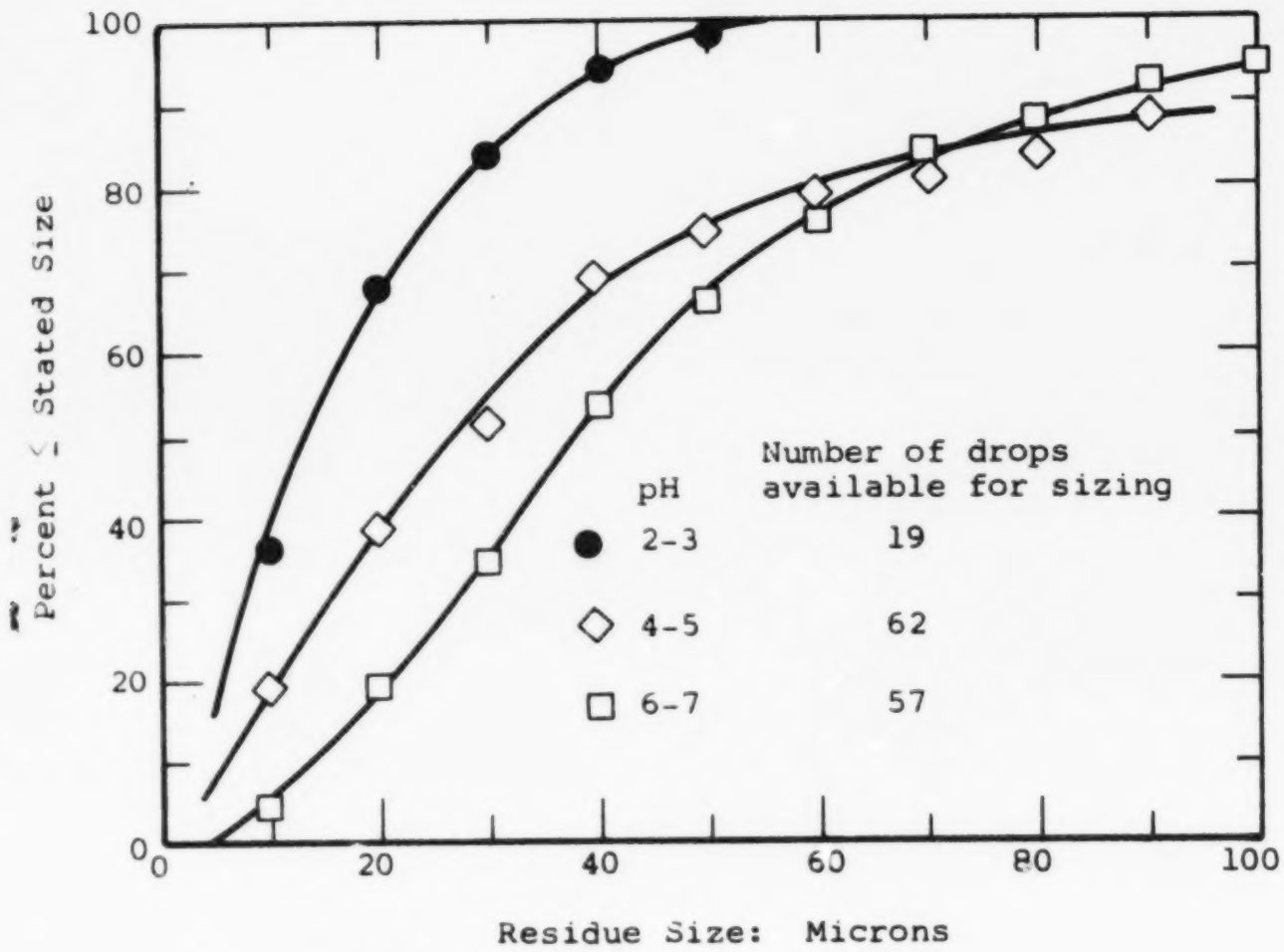


Figure C-2: Plume Droplet Resudue Size Distribution Sample Number 3.

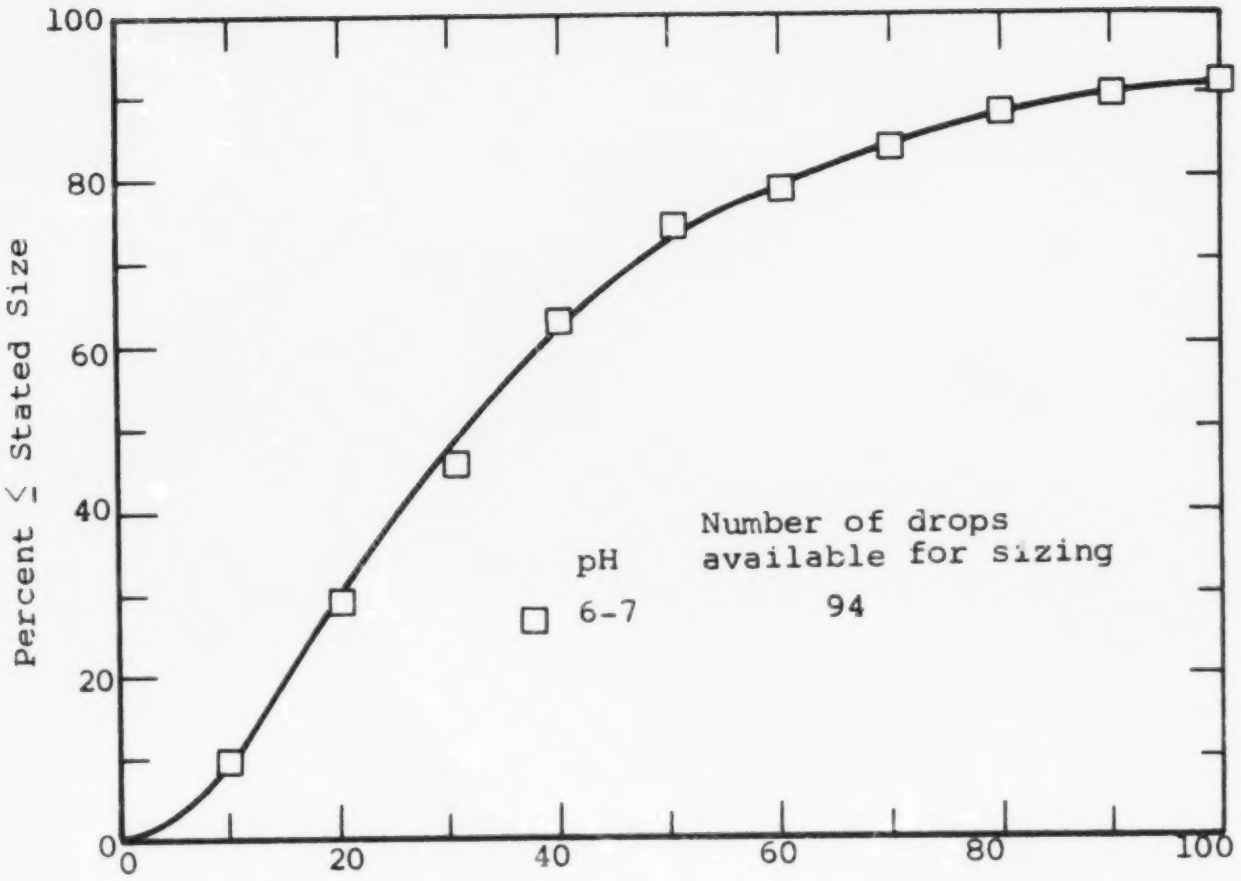


Figure C-3: Plume Droplet Residue Size Distribution
Sample Number 6.

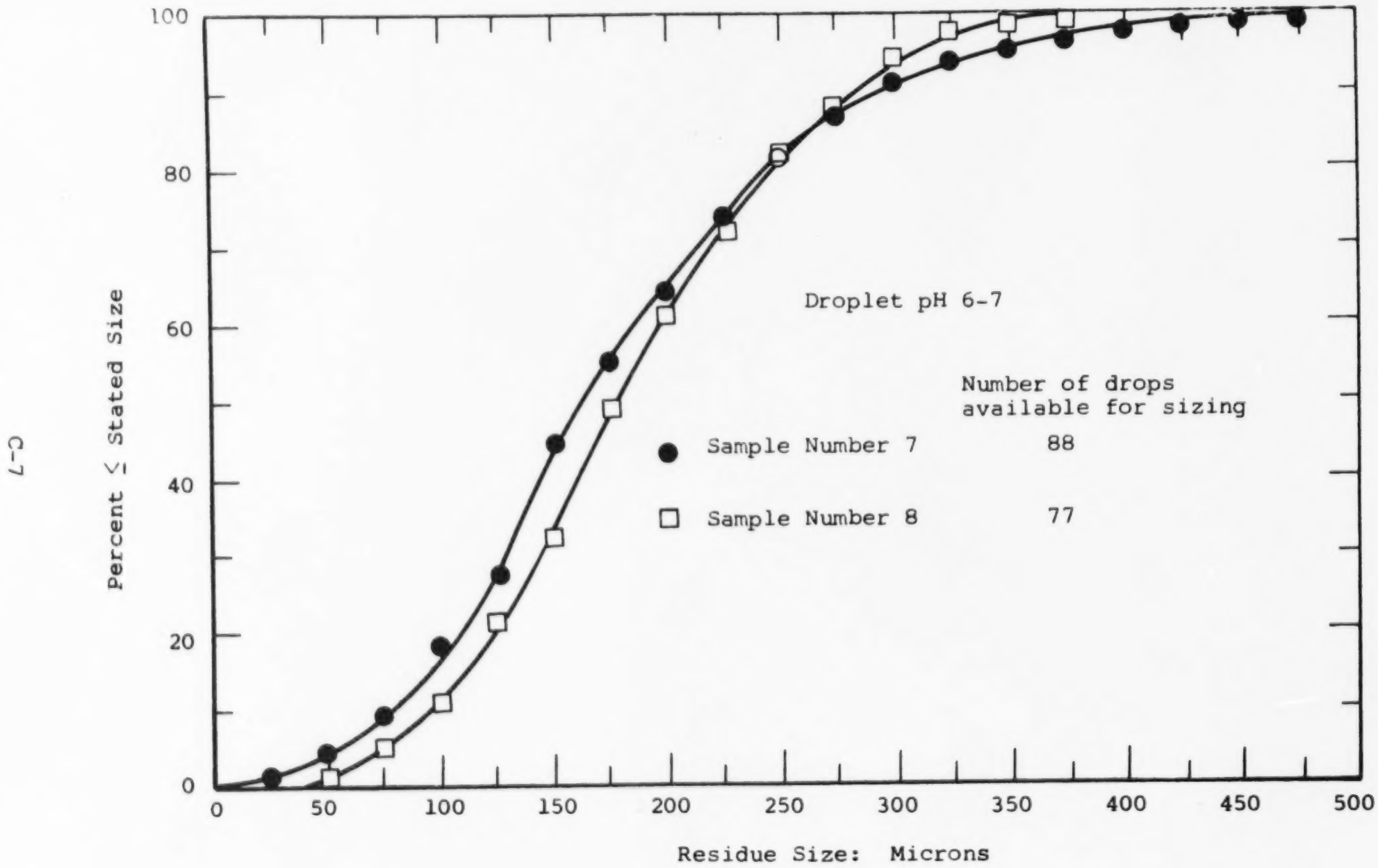


Figure C-4: Plume Droplet Residue Size Distribution. Sample Numbers 7 and 8.

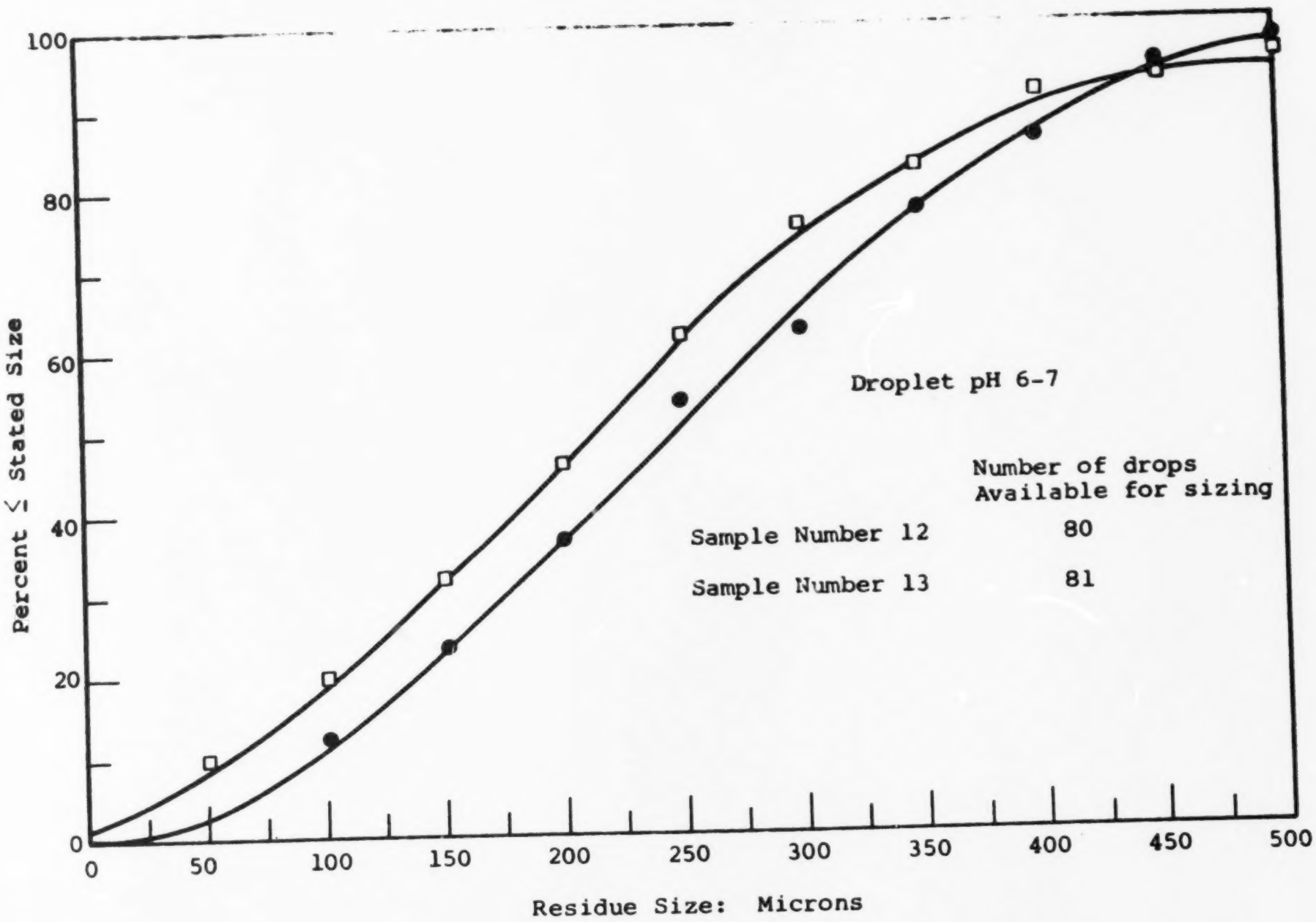
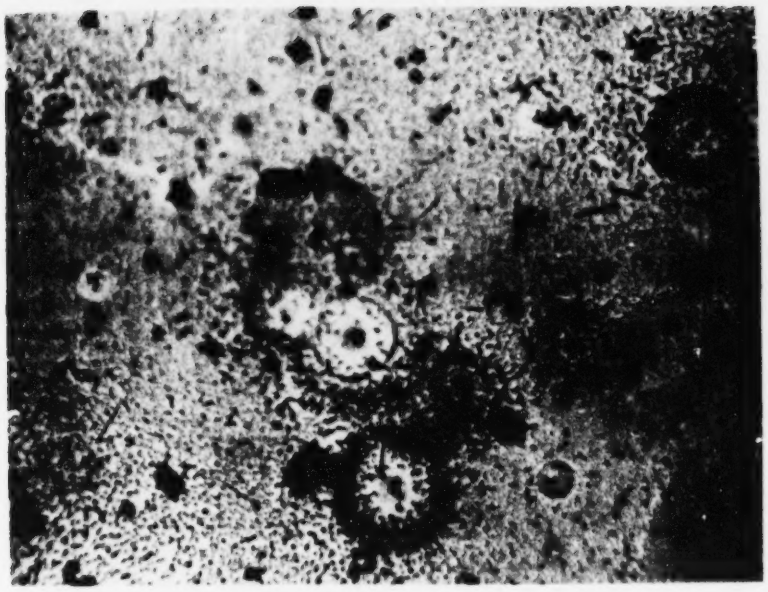
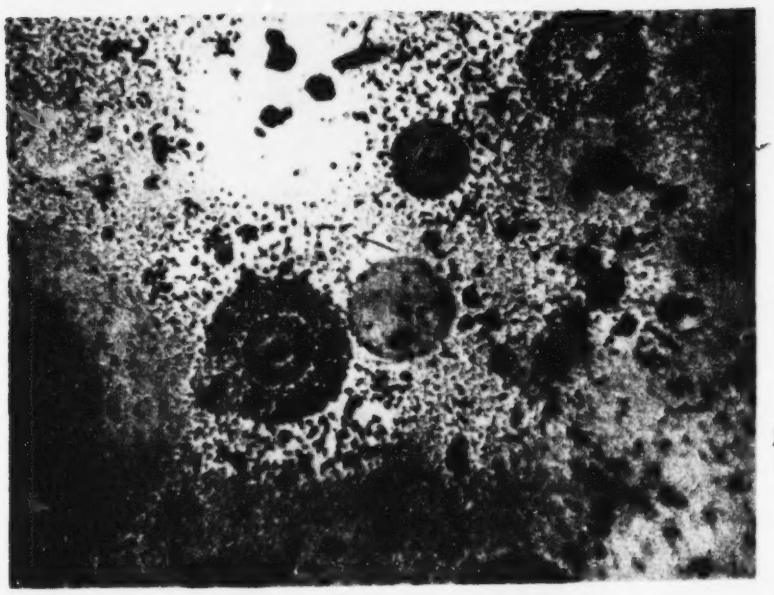


Figure C-5: Plume Droplet Residue Size Distributions. Sample Numbers 12 and 13.



NOT REPRODUCIBLE

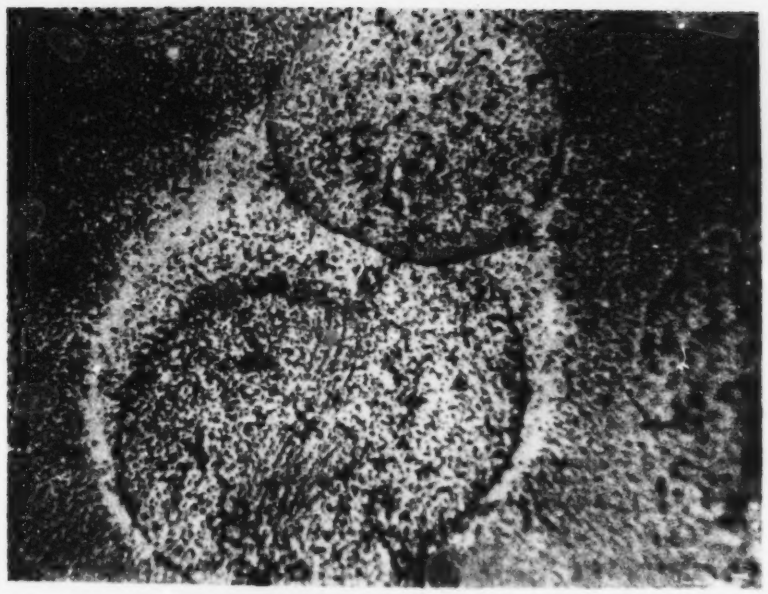


Scale: microns

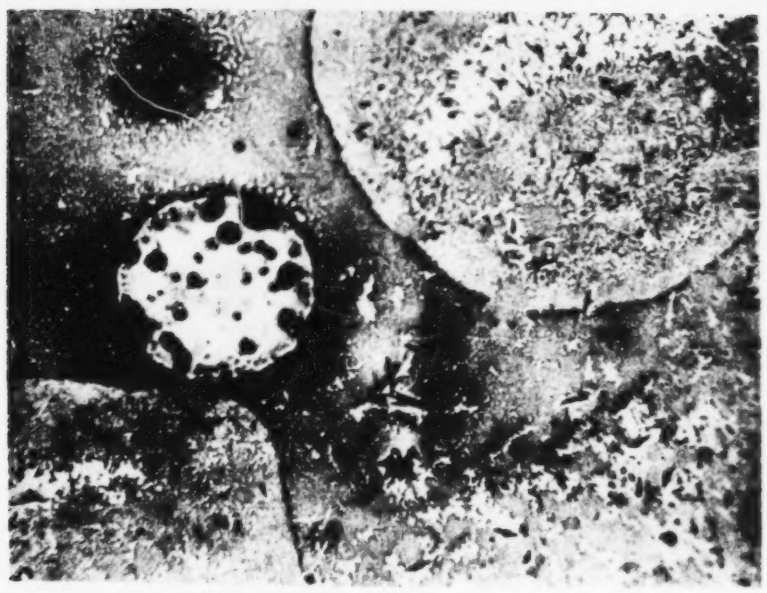
0 100 200

Plume Droplet Sample Number 2

Figure C-6: Tower and Stack Plumes Mixed. Droplets of pH 2-3, 4-5, 6-7 present.



NOT REPRODUCIBLE



Scale: Microns

0 100 200

Plume Droplet Sample Number 14

Figure C-7: Tower and Stack Plumes not Mixed pH of Droplets 6-7.

References

C-1. Waller, R. E., "Acid Droplets in Town Air," Int. J. Air Water Polln. 7, 773-8, 1963.

C-2. Liddell, H. F. and Wootten, N. W., "The Determination and Measurement of Water Droplets," Quart. J. Roy Meteorol. Soc. 83, p. 263, 1957.

Appendix D

Model Analysis of Moist Bent-Over Plumes

MODEL ANALYSIS OF MOIST BENT-OVER PLUMES

Since the vertical motion of a plume eventually becomes small and the horizontal motion is almost identical with that of the wind at the altitude of the plume, the plume bends over and becomes nearly horizontal at a sufficient distance downwind of the stack. The behavior of this part of the plume thus becomes the same as that of a cylindrical thermal. Solutions for simple cylindrical thermals rising in a neutral atmosphere have been applied to bent-over plumes by Scorer (Reference D-1). For the purpose of the problem considered here, this analysis is extended to include the latent heat of evaporation and condensation.

The equations governing the change of mass and momentum in a cylindrical thermal are:

mass

$$\frac{dR^2}{dt} = 2 \alpha R \left|\bar{w}\right| \tag{1}$$

momentum

$$\frac{d\, R^2\, \bar{w}}{dt} = g\, R^2\, \frac{\overline{\Delta\rho}}{\rho_\infty} \tag{2}$$

where

g = acceleration corresponding to gravity
R = effective plume radius
t = time
$\bar{w}$ = mean vertical velocity
α = entrainment coefficient - 0.433
$\overline{\Delta\rho}$ = mean density difference
ρ_∞ = density of atmosphere at same altitude.

The effective plume radius is a measure of the distance the plume extends from its natural axis such that the velocity and buoyancy can be expressed in the dimensionless form:

$$\frac{w}{\bar{w}} = f_1 \left(\frac{y-y_o}{R}, \frac{z-z_o}{R}\right) \qquad (3)$$

$$\frac{\Delta\rho}{\overline{\Delta\rho}} = f_2 \left(\frac{y-y_o}{R}, \frac{z-z_o}{R}\right) \qquad (4)$$

where

w = local vertical velocity

y = cross wind distance

z = vertical distance

Y_o, z_o = coordinate of plume axis

$\Delta\rho$ = local density difference.

The plume radius is shown not to require an interpretation of being a literal radius, but merely as being a reference dimension of the distance the plume extends from its axis.

To evaluate the effect of evaporation and condensation, the equations for ordinarily encountered cylindrical thermals are supplemented with an equation which is obtained from a water balance on the plume:

$$d\,\frac{(R^2 Y)}{dt} = 2\,\alpha\, Y_\infty\, R\left|\bar{w}\right| \qquad (5)$$

where

Y = mass fraction of water, vapor plus liquid, in plume

Y_∞ = mass fraction of water in atmosphere at the same altitude.

This equation merely states that the rate at which the water content of the plume increases is equal to the entrainment of water vapor from the atmosphere.

An energy equation for the plume may be derived from the partial differential equation for energy conservation:

$$\frac{\partial \theta}{\partial t} + \vec{u} \cdot \nabla \theta = \frac{\Omega'''}{\rho c_p} - \frac{1}{\rho c_p} \nabla \cdot \vec{q} \qquad (6)$$

where

c_p = specific heat at constant pressure

P = pressure

P_o = reference pressure at sea level

$\vec{q}$ = heat flow by conduction or turbulent convection

Ω''' = heat produced per unit volume by latent heat effects

θ = potential temperature = $T\ (P/P_o)^{-2/7}$ (7)

ρ = density.

Because consideration has to be given to a stably stratified atmosphere in which the potential temperature is not constant, it is more convenient to work with the difference between the potential temperature in the plume and in the atmosphere at the same altitude, than with the potential temperature itself. Thus:

$$\theta' = \theta - \theta_\infty \qquad (8)$$

where θ_∞ = potential temperature of atmosphere.

Substitution of Equations (8) and (6) gives:

$$\frac{\partial \theta'}{\partial t} + \vec{u} \cdot \nabla \theta' = w \frac{\partial \theta_\infty}{\partial z} + \frac{\Omega'''}{\rho c_p} - \frac{1}{\rho c_p} \nabla \cdot \vec{q} \qquad (9)$$

Integration of Equation (9) over a cross-section enclosing the plume gives:

$$\int \frac{\partial \theta'}{\partial t} dV + \int \vec{u} \cdot \nabla \theta' dV = \int \frac{\Omega'''}{\rho c_p} dV - \frac{\partial \theta_\infty}{\partial z} \int w\, dV$$

$$- \frac{1}{\rho c_p} \int \nabla \cdot \vec{q}\, dV \qquad (10)$$

where dV = volume element.

From the divergence theorem, the volume integrals can be expressed as equivalent surface integrals:

$$\int \nabla \cdot \vec{q}\, dV = \int \vec{q} \cdot \vec{n}\, dS \tag{11}$$

$$\int \vec{u} \cdot \nabla \theta'\, dV = \int \theta' \vec{u} \cdot \vec{n}\, dS \tag{12}$$

where

$\vec{n}$ = unit vector normal to the surface

dS = surface element.

From Equations (11) and (12), (10) becomes:

$$\int \frac{\partial \theta'}{\partial t}\, dV + \int \theta'\, \vec{u}\cdot\vec{n}\, dS = \int \frac{Q'''}{\rho c_p}\, dV$$

$$- \frac{\partial \theta_\infty}{\partial z} \int w\, dV - \frac{1}{\rho c_p} \int \vec{q} \cdot \vec{n}\, dS \tag{13}$$

Because the boundary of the region over which the integration was performed is outside of the plume, the temperature excess, θ', and heat flux, q, are both zero:

$$\int \frac{\partial \theta'}{\partial t}\, dV = \int \frac{Q'''}{\rho c_p}\, dV - \frac{\partial \theta_\infty}{\partial z} \int w\, dV \tag{14}$$

It is also possible to make the substitution:

$$\frac{d}{dt} \int \theta'\, dV = \int \frac{Q'''}{\rho c_p}\, dV - \frac{\partial \theta_\infty}{\partial z} \int w\, dV \tag{15}$$

The volume integrals are precisely related to the expressions appearing in Equations (1), (2), and (5) by the following:

$$\int w\, dV = R^2\, \bar{w} \tag{16}$$

$$\int \theta'\, dV = R^2\, \overline{\theta'} \tag{17}$$

$$\int Q'''\, dV = R^2\, \overline{Q'''} \tag{18}$$

where

$\overline{\theta'}$ = mean potential temperature excess

$\overline{Q'''}$ = mean heat production.

The plume energy equation may thus be expressed as:

$$\frac{d\, R^2\, \overline{\theta'}}{dt} = \frac{R^2\, \overline{Q'''}}{\rho c_p} - \frac{\partial \theta_\infty}{\partial z} R^2\, \bar{w} \qquad (19)$$

The production or loss of heat by condensation or evaporation is related to the change in the mass fraction of liquid water present as shown in the expression below:

$$Q''' = + \rho\, \Delta H\, \frac{d(R^2 Y_1)}{dt} \qquad (20)$$

where

ΔH = latent heat of vaporization

Y_1 = mass fraction of water present as liquid.

Substitution of Equations (20) in (19) gives:

$$\frac{d}{dt}\left[R^2\left(\theta' - \frac{\Delta H}{c_p} Y_1\right)\right] = - \frac{\partial \theta_\infty}{\partial z} R^2\, \bar{w} \qquad (21)$$

Rather than seek analytical solutions for Equations (1), (2), (5), and (21), they were programmed for numerical solution. A fourth order Runge Kutta method was used to perform the required integrations. At each step in the Runge Kutta integration, values are returned for the quantity designated as F, Equation (19)

$$F = \theta' - \frac{\Delta H}{c_p} Y_i$$

and the mass fraction of water, Y, (liquid plus vapor) Equation (5). The separate mass fractions of water in the liquid and vapor states were determined by the iterative procedure described below.

1. Assume no liquid water is present initially.
2. Calculate temperature from assumed liquid mass fraction.

$$\theta' = F + \frac{\Delta H}{c_p} Y_l$$

3. Calculate vapor pressure from value obtained for the temperature obtained in 2.

$$\text{Log } p_v = 8.1076 - 1750.3/(T+235)$$

T = temperature °C

p_v = vapor pressure, mm Hg

4. Calculate mole fraction of water vapor present.

$$x = \frac{p_v}{760 - p_v}$$

5. Calculate mass fraction of water vapor present.

$$Y_v = \frac{0.622\ x}{0.622\ x + 1 - x}$$

6. If the mass fraction of water from Equation (5) exceeds the mass fraction of water vapor calculated in step 5, calculate the fraction present as liquid.

$$Y_l = Y - Y_v$$

7. Go back to step 2 and repeat procedure with a new value of liquid mass fraction until assumed value agrees with value calculated in step 6.

The techniques described here were used to calculate the plume's altitude and properties for distances downwind of the tower where the vertical velocity was less than that of the wind at the altitude of the plume. Both visible and invisible regions of the plume were calculated. For that part of the plume close to the tower where the vertical velocity of the plume exceeded that of the wind, the plume's motion was calculated from the equations for vertical plumes given by Morton (Reference D-2). The partitioning of water between liquid and vapor phases was calculated by the same method used for horizontal plumes. In this calculation, the horizontal motion was also assumed equal to the speed of the wind.

The results obtained show the effects of buoyancy removed or created by evaporation or condensation of liquid water. This type of plume model is an entrainment model in which the admixture of ambient air into the plume takes place by the turbulence induced by the plume's motion. At sufficiently great distances from the tower, the admixture of ambient air by this mechanism falls below that due to the natural turbulence of the atmosphere; and it is more appropriate to a diffusion type model at these large distances.

Owing to the difficulty of measuring effluent conditions at the tower exit a detailed comparison between the modeling results and the observed plume behavior could not be made.

References

D-1. Scorer, R. S., "The Rise of Bent-Over Plumes," Advances in Geophysics, Vol. 6, Academic Press, 1959.

D-2. Morton, B. R., "Buoyant Plumes in a Moist Atmosphere," J. Fluid Mechanics 2, 1957.